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Technical Note N-900

CORROSION OF MATERIALS IN HYDROSPACE - PART I. IRONS, STEELS, CAST IRONS, AND STEEL PRODUCTS

BY

Fred M. Reinhart

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Internal Working Paper

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

CORROSION OF MATERIALS IN HYDROSPACE - PART I. IRONS, STEELS, CAST IRONS, AND STEEL PRODUCTS

Technical Note N-900

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ABSTRACT

A total of 1300 specimens of 47 iron base alloys were exposed at depths of 2,340, 2,370, 5,300, 5,640 and 6,780 feet at two sites in the Pacific Ocean for 197, 402, 1064, 123, 751 and 403 days respectively to determine the effects of deep ocean environments on their corrosion behavior.

Corrosion rates, pit depths, types of corrosion, changes in mechanical properties, effects of stress, and analyses of corrosion products are presented.

The corrosion rates of all the alloys, both cast and wrought, decreased asymptotically with duration of exposure and became constant at rates varying between 0.5 and 1.0 mils per year after three years of exposure in sea water and partially embedded in the bottom sediments at a nominal depth of 5,500 feet. These corrosion rates are about one-third those at the surface in the Atlantic Ocean.

At the 2,350 foot depth, the corrosion rates in sea water also decreased with duration of exposure but tended to increase slightly with duration of exposure in the bottom sediments.

The corrosion rates at the 2,350 foot depth were less than those at the 5,500 foot depth.

The mechanical properties were unimpaired.

Silicon and silicon-molybdenum cast irons were uncorroded.

A sprayed 6 mil thick coating of aluminum protected steel for a minimum of three years and a hot dipped 4 mil thick coating of aluminum protected steel for a minimum of 13 months while a hot dipped 1.7 mil thick coating of zinc protected steel for about 4 months.

The performance of metallic coated and uncoated wire ropes and cables is also discussed.

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FIGURES

INTRODUCTION

Recent interest in, and emphasis on the deep ocean as an operating environment has created a need for information about the behavior of constructional materials in this environment.

The Naval Facilities Engineering Command of the Office of Naval Materiel is charged with the responsibility for the construction of all fixed Naval facilities, including the construction and maintenance of Naval structures at depths in the oceans.

Fundamental to the design, construction and operation of structures, and their related facilities, is information about the deterioration of materials in the deep ocean environments. This report is devoted to the effects of these environments on the corrosion of metals and alloys.

A test site was considered to be suitable if the circulation, sedimentation, and bottom conditions were representative of open ocean conditions: (1) the bottom should be reasonably flat, (2) the site should be open and not located in an area of restricted circulation such as a silled basin, (3) the site should be reasonably close to Port Hueneme for ship operations, and (4) the site should be within the operating range of the more precise navigation techniques.

A site meeting these requirements was selected at a nominal depth of 6,000 feet. The location of this site in the Pacific Ocean in relation to Port Hueneme and the Channel Islands is shown in Figure 1 as Submersible Test Units (STUs) I-1, I-2, I-3, and I-4.

The environmental conditions at the bottom, a depth of 5,650 feet at a location about 5 miles northwest of STU I-1 were reported to be as follows:[1]

1. Temperature 2.53°C
2. Salinity 34.58 ppt
3. Oxygen 1.29 ml/1

The complete oceanographic data for Site I are shown graphically in Figure 2.[2,3] A portion of this data collected from 1961 to 1963 showed the presence of a minimum oxygen zone (as shown in Figure 2) at depths between 2,000 and 3,000 feet. Oceanographic data obtained at other Pacific Ocean sites also showed the presence of this minimum oxygen zone regardless of depth to the ocean floor.

Corrosion rates are affected by the concentration of oxygen in the environment. Therefore, it was decided to establish a second

exposure site (STU II-1 and II-2) in the minimum oxygen zone at a nominal depth of 2,500 feet. This site is also shown in Figure 1.

A summary of the characteristics of the waters approximately 10 feet above the bottom at the different exposure sites is given in Table 1.

The NCEL oceanographic investigations also disclosed that the ocean floor at each of these sites was rather firm and was characterized as sandy, green cohesive mud (partially glauconite) with some rocks. The biological characteristics of this sediment are described in References 4 through 8.

The details of the construction, emplacement and retrieval of the STU structures are given in References 9 through 12.

The procedures for the preparation of the specimens for exposure and for evaluating them after exposure are described in Reference 13.

Previous reports pertaining to the performance of materials in the deep ocean environments are given in References 13 through 17.

This report presents and discusses the results obtained from exposure of irons, steels, low alloy steels, alloy steels, unalloyed and alloyed cast irons, steel wire ropes, anchor chains and metallic coated products for six periods of time and at two nominal depths shown in Table 1.

RESULTS AND DISCUSSION

The chemical composition of the irons, mild steels, high-strength low-alloy steels, alloy steels, high strength steels, nickel steels, alloy cast irons, austenitic cast irons, etc., are given in Table 2; their surface conditions and heat treatments, if any, are given in Table 3.

Included in Table 2 are the chemical compositions of the iron base alloys which were exposed on the STU structures for the International Nickel Company, Inc. Dr. T. P. May, Manager, Harbor Island Corrosion Laboratory of the International Nickel Company, Inc. has granted permission to incorporate his corrosion data (Reference 18), obtained from their specimens on the six STU structures, with the NCEL data.

Some additional data from another participant in the NCEL exposures, Aeronautical Materials Laboratory, are also included, (Reference 19).

Surface data of some alloys of chemical compositions similar to those in Table 2 from the Atlantic Ocean (Reference 20) and similar to those from the Panama Canal Zone, Pacific Ocean (Reference 21) are

included for comparison purposes. Deep ocean data from the Atlantic Ocean is also included to permit comparison of the different deep ocean environments, References 22 - 24.

The corrosion rates and types of corrosion of all the metals are given in Table 4. In the column designated "Crevice" an intentional crevice was created on one specimen of each alloy by bolting a 1-inch square piece of the same alloy to the specimen with a nylon nut and bolt. The corrosion rates of some of the alloys are shown graphically in Figures 3 through 21.

Water in the open sea is quite uniform in its composition throughout the oceans;[26] therefore, the corrosion rates of steels exposed under similar conditions in clean sea water should be comparable. The results of many investigations on the corrosion of structural steels in surface sea water at many locations throughout the world show that after a short period of exposure the corrosion rates are constant and amount to between 3 and 5 mils per year.[21,27,28] Factors which may cause differences in corrosion rates outside these limits are variations in marine fouling, contamination of the sea water near the shorelines, variations in sea water velocity, and differences in the surface water temperature.

IRONS AND STEELS

Corrosion

The corrosion rates of low carbon steels in sea water at different locations as indicated below are compared in Figure 3:

a. Surface waters of the Atlantic Ocean at Harbor Island, North Carolina;[20]

b. Surface waters of the Pacific Ocean at Fort Amador, Panama Canal Zone;[21]

c. Deep Atlantic Ocean waters, Tongue-of-the-Ocean, Bahamas;[22,23,24]

d. Deep Pacific Ocean waters, Port Hueneme, California.

The corrosion rates of the steels at the surface in both the Atlantic and Pacific Oceans decrease rather rapidly with time and become relatively constant after about 2 to 3 years of uninterrupted exposure. The higher corrosion rates at Fort Amador are attributed to the difference in temperature between the two sites (27°C vs 21°C).

The corrosion rates of the steels exposed at nominal depths of 5,500 and 2,350 feet in the Pacific Ocean also decreased with time of exposure and were consistently lower than the surface corrosion rates. These lower corrosion rates are attributed to the combined effects of the differences between the variables at the surface and at the two depths; temperature, pressure and oxygen concentration.

Also, the corrosion rates at a depth of 2,350 feet were lower than those at a depth of 5,500 feet. In this case, the lower corrosion rates at a depth of 2,350 feet are attributed to the combined effects of the differences between the variables at the two depths; temperature, pressure and oxygen concentration, Table 1.

Because of the interdependence of one variable on another, the above differences in the corrosion rates cannot be attributed chiefly to any one variable. For example, the solubility of oxygen in sea water is increased as the pressure is increased at constant temperature but at constant pressure the solubility of oxygen decreases as the temperature increases.

In their discussion of the effect of temperature, the interdependence of the effect of temperature and other rate factors on corrosion is discussed by LaQue and Copson state:[29] "In general, the effect of temperature on the corrosion rate depends on its influence on the factors controlling the corrosion reaction. Temperature may affect the corrosion rate through its effect on oxygen solubility and availability. As the temperature rises the oxygen solubility in an aqueous solution decreases. Opposed to this is the fact that the diffusion rate of oxygen increases with temperature. The corrosion rate of steel in aqueous solutions with free access of air reaches a maximum at about 175°F. On the other hand, in a closed system where the pressure was allowed to increase, the corrosion rate increased linearly at about 3 percent per degree which suggests control by the diffusion rate of oxygen to the steel. Temperature may affect corrosion through its effect on pH. The dissociation of water increases with temperature with the result that the pH decreases with temperature (becomes more acid). Temperature may also affect corrosion rate through its effect on films. It may increase the solubility of corrosion products in some cases in other cases cause the precipitation of protective films and in still other situations change the characteristics of corrosion products to render them more impervious to oxygen diffusion." According to H. H. Uhlig:[30] "When corrosion is controlled by diffusion of oxygen, the corrosion rate, at a given oxygen concentration, approximately doubles for every 30°C rise in temperature." However, LaQue[31] has pointed out that in flowing

sea water, when no fouling organisms become attached to small, fully immersed specimens, corrosion of steel at 11.1°C proceeded at 7 MPY compared with 14 MPY at 21.1°C. This increase (twofold) corresponds with what would be expected from chemical kinetics, where the rate of reaction is approximately doubled for a rise of 10°C.

Uhlig[30] has shown that the corrosion rate of iron in air saturated water is proportional to the oxygen concentration. He has also conducted experiments in the laboratory which show that at constant temperature the corrosion rate of steel in a calcium chloride solution increases in direct proportion to increase in oxygen concentration.

When steel is in free contact with sea water its corrosion rate increases as the velocity of the water increases.[27]

Within the range of about pH 4 to 10, the corrosion rate of steel in aerated water at room temperature is independent of pH, and depends only on how rapidly oxygen diffuses to the metal surface.[30]

L. L. Schreir[32] states: "It is a remarkable and important fact that except where there is gross dilution or contamination, the relative proportions of the major constituents of sea water are practically constant all over the world." "In the major oceans the salinity of sea water does not vary widely, lying in general between 33 and 37 parts per thousand; 35 parts per thousand is commonly taken as the average for "open-sea" water." Nevertheless, the corrosion rates at a depth of 5,500 feet in the Pacific Ocean were about one-third the rate of the steels at Harbor Island after about 3 years of exposure.

Variables which were different between the surface in the Atlantic Ocean at Harbor Island, North Carolina, and at a depth of 5,500 feet in the Pacific Ocean are given in Table 5. The current at the surface was variable in direction and magnitude, being due only to normal tidal action; at depth in the Pacific Ocean there was practically no current; hence, there was probably very little effect due to differences in current alone. As discussed above, the difference in pH between the two sites would be expected to be ineffectual. Hence, the difference in corrosion rates is attributed to differences in pressure, temperature and oxygen concentration.

The corrosion rates for a steel exposed by the Naval Research Laboratory at a depth of 5,600 feet in the Tongue-of-the-Ocean in the Atlantic were slightly higher than those in this investigation, Figure 3. Oceanographic data reported for the Tongue-of-the-Ocean are: depth, 4,967 feet; 4.18°C and 5.73 ml/l oxygen.[33] Since the differences between the depths, pressures and temperatures are small the higher corrosion rates in the Atlantic are attributed chiefly to the difference in the concentration of oxygen between the two

locations (5.73 vs 1.4 ml/1) with the possibility that some of the corrosion might be due to the difference in the currents (unknown in the Atlantic but practically stagnant in the Pacific). The difference between the corrosion rates on the surface at Harbor Island, N. C. and at a depth of 5,600 feet in TOTO is attributed to differences in depth (pressure, 0 vs 2520 psi) and temperature (19°C vs 4.2°C).

Corrosion rates for steel at a depth of about 4,500 feet[23,24] in TOTO were practically the same as those at the surface at Harbor Island for comparable periods of time.

The corrosion rates of wrought iron and Armco iron at depths were comparable with those of AISI 1010 steel as shown in Figure 4. The corrosion rate of wrought iron at the surface at Fort Amador in the Pacific Ocean Panama Canal Zone[25] after about 3 years of exposure was approximately 7 times greater than at a depth of 5,500 feet in the Pacific Ocean.

The corrosion rates of all the alloy steels at depths of 5,500 and 2,350 feet in sea water are shown in Figure 5. These values are shown as shaded areas encompassing most of the values. The corrosion rates for these steels decreased similarly to those for carbon steel with time of exposure at both depths. Although the corrosion rates at a depth of 5,500 feet varied between 1.9 and 6.0 MPY after 123 days of exposure they were all essentially the same after 1,064 days of exposure (0.5 to 0.9 MPY). The performance of these same steels when partially embedded in the bottom sediments is shown in Figure 6. After 1,064 days of exposure at a depth of 5,500 feet, the corrosion rates were the same as those in the sea water above the bottom sediments. However, the corrosion rates for many of the steels after 403 days of exposure in the bottom sediment at a depth of 6,780 feet were less than 0.5 MPY; this is attributed to the greater proportion of each specimen that was embedded in the bottom sediment. The specimens of these particular steels were about 2 inch diameter discs and in all probability were nearly completely embedded in the bottom sediment.

The data for all the steels was analyzed statistically. The mean curve of the corrosion rates and 95 percent confidence limits are shown in Figure 7 for the specimens exposed in the sea water and in Figure 8 for the specimens partially embedded in the bottom sediments. The corrosion rate curves for AISI 1010 steel and high-strength-low alloy steel #2 exposed at a depth of 5,600 feet in TOTO are also included to reveal that they are outside the 95 percent confidence limits. The fact that they are outside the 95 percent confidence limits

of the corrosion rates of the steels exposed at a depth of 5,500 feet in the Pacific Ocean indicates that the environment in the Atlantic Ocean is somewhat different from the environment in the Pacific Ocean. The median curve of corrosion rates for the 2,350 foot depth is below that for the 5,500 foot depth indicating a difference in environments even though the confidence limits overlap. In the case of the median corrosion rates curves for the specimens in the bottom sediments (Figure 8), the median values are the same after 400 days of exposure indicating that the environments are nearly identical. The median corrosion rate curves for the 2,350 foot and 5,500 foot depths are shown in Figure 9. Between 200 and 400 days of exposure the corrosiveness of the bottom sediment at 5,500 feet was the same as the sea water at the 2,350 foot depth. After 400 days of exposure the bottom sediments at the 5,500 foot and 2,350 foot depths and the sea water at the 2,350 foot depth were of equal aggressiveness. After 751 days of exposure at the 5,500 foot depth, the sea water and bottom sediment environments were similar with regard to their effect on the corrosion of steels. Since no data are available for the 2,350 foot depth for periods of exposure beyond 400 days it is not possible to correlate the corrosion of steels at the two depths beyond this duration of exposure.

Variations of from 1.5 to 9 percent in the nickel content of steel were ineffectual with respect to the corrosion rates as shown in Figure 10.

The corrosion rates of AISI Type 502 steel (5% Cr-0.5% Mo) were erratic and higher than for the other steels. This behavior is attributed to the broad shallow pitting and severe crevice corrosion at insulators and fasteners.

The corrosion rate for a nickel-cobalt high strength (190 KSI) alloy steel was within the limits shown for other alloy steels in Figure 5 for 402 days of exposure at a depth of 2,370 feet.

Specimens of two heats of 18% Ni maraging steels from NCEL and one heat from INCO were exposed for 402 days at a depth of 2,370 feet. The 0.08 inch thick material from one NCEL heat was aged at 900°F for three hours and air cooled, then a portion was welded. This material, both unwelded and welded corroded at twice the rate of the material from the other heats, 3.2 MPY vs 1.4 MPY. The material aged by NCEL had a yield strength of 315 KSI while the yield strengths of the heats aged by the producer were in the range of 235 to 265 KSI. The corrosion was uniform with tightly adhering films of black corrosion products.

The data in the column labeled "Crevice" in Table 4 show that there were no significant changes in the corrosion rates of these alloys due to crevice corrosion. Although crevice corrosion is reported in some cases, the intensity and amount was not great enough to significantly change the corrosion rate of that particular alloy.

Stress Corrosion

Some of the steels were exposed in the stressed condition at values equivalent to 35, 50 and 75 percent of their respective yield strengths. The steels, stresses, depths, days of exposure and the susceptibility to stress corrosion cracking are given in Table 6. None of these steels were susceptible to stress corrosion cracking for the periods of time exposed at the various depths.

Mechanical Properties

The percent changes in the mechanical properties of the exposed steels are given in Table 7. There were no significant changes in the mechanical properties due to corrosion except for the AISI Type 502 steel. The decreases in elongation, 34-38 percent, of the AISI Type 502 steel were considered significant and were attributed to the pitting corrosion.

Corrosion Products

The corrosion products from some of the steels were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis and infrared spectrophotometry. The constituents found were:

Alpha iron oxide - $Fe_2O_3 \cdot H_2O$

Iron hydroxide - $Fe(OH)_2$

Beta iron (III) oxide hydroxide - FeOOH

Iron oxide hydrate - $Fe_2O_3 \cdot H_2O$

Significant amounts of chloride, sulphate and phosphate ions.

Anchor Chains

Two types of 3/4 inch anchor chain, Dilok and welded stud link, were exposed at the depths and for the periods of time shown in Table 1. The chain links were covered with layers of loose, flaky rust after each exposure. The layers varied from thin to thick as the time of exposure increased. Destructive testing of the exposed chain links (Table 8) showed no decrease in the breaking loads of the links for periods of exposure of at least 1,064 days. Hence, there was no impairment of the strength of either of the chains. The Dilok links all failed at the bottoms of the sockets where the cross-sectional area of the steel was the smallest. Rust was present in all these broken sockets indicating that sea water had penetrated the joints. Stagnant sea water in these sockets for prolonged periods of time could result in destruction of the links due to the internal stresses created by the formation of corrosion products.

Wire Rope

A number of metallic wire ropes were exposed at various depths and for different periods of time as shown in Table 9. These were plow steel, galvanized steel, aluminized steel, stainless steel and 90 copper-10 nickel clad stainless steel ropes and cables of different types of construction.

The first three ropes in Table 9 were for an evaluation of the effect of plastic tape on the corrosion and strength of a conventional wire rope. The breaking strengths were the same after exposure and were in agreement with published nominal values for this type of rope. There was more rust on the inside strands of the degreased rope than on the one in the "as received" (lubricated) condition. For a distance of about 3 feet from the eyes there was considerably more rust underneath the polyethylene tape, than on the degreased rope. About 50 percent of the inside strands were rusted at the break in the rope. This test indicates that no corrosion protection is afforded by taping when sea water has access to the interface between the rope and the tape.

The zinc on the 0.125 inch diameter, 7 x 19 construction, lubricated galvanized aircraft cable was completely covered with red rust after 403 days of exposure at a depth of 6,780 feet. In addition, the breaking strength had decreased by 50 percent.

The amount of zinc remaining on the other five galvanized ropes varied from none in the case of the 0.094 inch diameter, 7 x 7 cable

which was 100 percent rusted on the outer surfaces to considerable remaining on the 0.25 inch diameter, 7 x 19 construction cable which was dark gray. There was no loss in the breaking strength of any of these five cables.

After 403 days of exposure at a depth of 6,780 feet the smaller diameter (0.094, 0.125 and 0.187 inch diameter) stainless steel cables lost considerable strength, 90, 86, and 96 percent respectively. These decreases were all attributed to crevice corrosion of the internal wires. Many pits were also found on the individual wires away from the breaks and some broken ends were protruding from the cables prior to testing.

There was no loss in breaking strength of the three larger diameter stainless steel cables, the inside strands were chiefly metallic color with only a few localized rust spots.

Two types 304 stainless steel cables clad with a 90 percent copper-10 nickel alloy were exposed for 402 days at a depth of 2,370 feet. One cable, 1 x 37 x 7 construction with a 0.3 mil thick clad layer was covered with rust on the outside but the inside wires were uncorroded. The other cable, 7 x 7 construction with a clad layer 0.7 mil thick was covered with green corrosion products on the outside, uncorroded on the inside strands and had lost no strength.

Three aluminized steel cables (7 x 7, 1 x 19 and 1 x 19 construction) with 0.6, 0.6 and 0.7 mil thick coatings lost no strength during the 402 day exposure at a depth of 2,370 feet. The 7 x 7, 0.187 inch diameter cable was covered with white corrosion products and a few light rust stains but the inside strands were dull gray in color. The outside surfaces of the 1 x 19 construction wires (0.250 and 0.313 inch diameter) were gray in color with scattered white corrosion products covering about 50 percent of the surfaces. The inside strands were a dull gray color.

Eight wire ropes were stressed in tension equivalent to approximately 20 percent of their respective original breaking strengths as shown in Table 10. There were no stress corrosion failures after either 751 or 1,064 days of exposure. However, the breaking strength of the Type 316 wire rope lost 40 percent of its strength after 1,064 days of exposure at a depth of 5,300 feet because of crevice corrosion of the internal wires. The breaking strength of the galvanized plow steel (0.83 oz Zn) was decreased by 17 percent. The breaking strengths of the other six wire ropes were unaffected. Although there was no loss in the breaking strength of the 18 percent chromium-14 percent manganese stainless steel rope there were quite a number of broken wires due to corrosion both on the outside and on the inside strands.

Metallic Coatings

Zinc, aluminum, sprayed aluminum and titanium-cadmium coated steel specimens were exposed at depth.

The galvanized steel (1.0 oz per sq ft) was covered with a layer of flaky red rust after 402 days of exposure at a depth of 2,370 feet. The corrosion rates were 0.9 MPY for the specimens exposed in the sea water and 0.4 MPY for the specimens partially embedded in the bottom sediment. The corrosion rate for bare steel (AISI 1010) in sea water under the same conditions was 1.2 MPY indicating that the zinc coating was removed within a short period of time (3 to 4 months). The difference in corrosion rates in the bottom sediment was 0.7 MPY which shows that the zinc coating protected the steel in the bottom sediment for at least twice as long as it did in the sea water. There was no loss in the mechanical properties of the galvanized steel.

The aluminized steel (1.03 oz per sq ft) was covered with white corrosion products, spotted with a few specks of red rust after 402 days of exposure at a depth of 2,370 feet. About 22 percent of the aluminum coating was corroded from the specimens exposed in the sea water and 40 percent was corroded from the specimens partially embedded in the bottom sediment; the underlying steel had not corroded. Therefore, it can be concluded, on a weight basis, that 1 oz per sq ft of aluminum will protect steel for a longer period of time than 1 oz per sq ft of zinc; about 4 times as long in sea water and about 2 times as long when partially embedded in the bottom sediment.

A titanium-cadmium coating on AISI 4130 steel was completely sacrificed and the steel was covered with a layer of red rust after 402 days of exposure at a depth of 2,370 feet.

A 6 mil thick, sprayed aluminum coating which had been primed and sprayed with 2 coats of clear vinyl sealer protected the underlying steel for 1,064 days of exposure at a depth of 5,300 feet. After removal from exposure the aluminum coating was dark gray in color, speckled with pin point size areas of white corrosion products.

Cast Irons

The chemical compositions of the cast irons are given in Table 1 and their corrosion rates in Table 4.

The corrosion rates for the gray, nickel, nickel-chromium, silicon, silicon-molybdenum and ductile cast irons at the two nominal depths in

the Pacific Ocean are shown graphically in Figure 11 for sea water and in Figure 12 for the bottom sediments.

There was no measurable corrosion of the silicon and silicon-molybdenum cast irons at either depth.

In sea water at both depths the other cast irons behaved similarly to the steels as is clearly shown by comparing the curves in Figure 5 with those in Figure 11. This similarity also obtains for the specimens partially embedded in the bottom sediment at the 5,500 foot depth; compare Figure 6 with Figure 12. At the 2,350 foot depth there is an anomaly in that the corrosion rates of the cast irons increase with time (Figure 12) whereas those of the steels tend to be constant with time. The reason for this increase is not apparent at this time.

The corrosion rates of the austenitic cast irons in sea water are shown graphically in Figure 13 and in the bottom sediment in Figure 14. The corrosion rates of these alloys in sea water also decrease with time of exposure at both depths with the rates at 2,350 feet being lower than those at 5,500 feet. However, such was not the case in the bottom sediments. For some presently inexplainable reason the corrosion rates after 400 days of exposure at a depth of 6,780 feet were much lower than after 750 days of exposure at a depth of 5,640 feet as well as slightly lower than after 1,064 days of exposure at a depth of 5,300 feet. This is the only group of alloys which behaved in this manner. At a depth of 2,350 feet the average corrosion rates were about the same for both periods of exposure and, again, were lower than for the other groups of alloys except the cast irons after 200 days of exposure (Figure 12).

The statistical curves and the 95 percent confidence limits for the two groups of cast irons both in the water and the bottom sediments are shown in Figures 15, 16 and 17. Very few values were outside the 95 percent confidence limits; one value after 1,064 days of exposure in the bottom sediment at 5,500 feet, one value after 197 days of exposure in the sea water at 2,350 feet, one after 400 days of exposure in the bottom sediment at 5,500 feet and one after 400 days of exposure in the bottom sediment at 2,350 feet.

Mechanical Properties

The percent changes in the mechanical properties of the exposed cast irons are given in Table 7. The mechanical properties of Ni-Resist No. 4 were not affected but those of Ni-Resist D-2c were significantly lowered.

About 80 percent of the surfaces of fracture of each broken tensile specimen was black in color and the other 20 percent was gray, in contrast to entirely gray surfaces of fracture for unexposed specimens. Metallographic examinations of surfaces normal to and at the edge of fracture showed that selective corrosion of an intermetallic constituent had occurred which caused the reduction in the mechanical properties.

The median curves for the two groups of cast irons and the alloy steels are shown in Figure 18 for sea water and in Figure 19 for bottom sediments. These curves (Figure 18) show that in sea water at a depth of 5,500 feet corrosion behavior of these three groups of alloys was the same after 750 days of exposure. There was a slight decrease in the corrosion rates of the three groups of alloys with time at a depth of 2,350 feet and the corrosion rate of each group was lower than that of its companion group at a depth of 5,500 feet. In the bottom sediments the behavior of the alloys was somewhat erratic. The lower corrosion rates after 400 days at a depth of 6,780 feet is attributed to the fact that a greater proportion of each specimen was embedded in the bottom sediment than during the other three exposure periods at the nominal depth of 5,500 feet. The corrosion rates at 2,350 feet tended to increase slightly with time for the steels and austenitic cast irons while those for the cast irons increased sharply. The type of behavior for the cast and wrought alloys can only be attributed to their proximity to the water-sediment interface or the percent embedment in the bottom sediment.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine the effects of deep ocean environments on the corrosion of irons, steels and cast irons. To accomplish this, specimens of 47 different alloys were exposed at nominal depths of 2,350 and 5,500 feet for periods of time varying from 123 to 1,064 days.

The corrosion rates of all the alloys, both cast and wrought, decreased asymptotically with time and became constant at rates varying between 0.5 and 1.0 MPY after three years of exposure at a nominal depth of 5,500 feet in sea water. These corrosion rates are about one-third those of wrought steels at the surface in the Atlantic Ocean at Harbor Island, North Carolina. The corrosion rates of these same alloys in sea water at a depth of 2,350 feet were lower than those at the 5,500 foot depth and decreased with time.

In general, the corrosion rates of all the alloys exposed either adjacent to or partially embedded in the bottom sediments at the 5,500 foot depth decreased asymptotically with time and became constant at rates between 0.5 and 1.0 MPY after three years of exposure. The corrosion rates of the alloys in the bottom sediments at the 2,350 feet depth tended to increase with time.

The corrosion rate of steel was not affected by nickel additions to 9 percent at either depth.

Silicon and silicon-molybdenum cast irons were immune to corrosion in deep ocean environments.

Type 502 steel was selectively attacked resulting in broad shallow pits and crevice corrosion, and its mechanical properties were impaired.

The mechanical properties of the other alloys were not impaired.

None of the steels were susceptible to stress corrosion cracking at stresses equivalent to 75 percent of their respective yield strengths.

The corrosion products of the alloys were composed chiefly of alpha iron oxide, ferric oxide hydrate, ferrous hydroxide and Beta iron (III) oxide-hydroxide.

Zinc (hot-dipped) (1.7 mils) and titanium-cadmium coatings failed to protect sheet steel for one year of exposure.

A hot-dipped aluminum coating (4 mils) protected sheet steel for a minimum of one year whereas a sprayed aluminum coating (6 mils, sealed) protected sheet steel for three years.

The mechanical properties of anchor chains were unimpaired. However, sea water penetrated the forged sockets of one type of chain as evidenced by corrosion at the bottoms of the sockets.

The mechanical properties of Type 304 stainless steel cables in sizes 0.094, 0.125 and 0.187 inch diameter were decreased by a minimum of 85 percent due to corrosion of the internal wires while those of the larger diameter wires were unaffected.

The breaking strength of a Type 304 stainless steel cable coated with 90 percent copper-10 percent nickel was not affected.

The breaking strengths of the aluminum coated steel wire ropes were unaffected.

The bare steel, zinc and aluminum coated steel and stainless steel wire ropes were not susceptible to stress corrosion cracking when stressed at 20 percent of their respective breaking loads. However, the Type 316 stainless steel wire rope lost 40 percent of its breaking strength due to corrosion of the internal wires.

The breaking strengths of bare steel, zinc and aluminum coated

steel wire ropes, both stressed and unstressed, were unimpaired by exposure to deep ocean environments for periods of time as long as 1,064 days. However, based on visual observations zinc coatings corroded at faster rates than aluminum coatings on the wire ropes.

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Table 1. STU Locations and Bottom Water Characteristics[1]

Site No.	Lat. N	Longit. W	Depth of STU, (ft)	Pressure, psi	Exposure, Days	Temp °C	Oxygen, ml/l	Salinity, ppt	pH	Current, Knots, Av.
Surface	-----	-----	65	29	-----	11-17	5.4-6.5	33.76	7.9-8.3	Variable
I-1	33°46'	120°37'	5300	2385	1064	2.6	1.2	34.51	7.5	0.03
I-2	33°44'	120°45'	5640	2538	751	2.3	1.3	34.51	7.6	0.03
I-3	33°44'	120°45'	5640	2538	123	2.3	1.3	34.51	7.6	0.03
I-4	33°46'	120°46'	6780	3051	403	2.2	1.6	34.40	7.7	0.03
II-1	34°06'	120°42'	2340	1053	197	5.0	0.4	34.36	7.5	0.06
II-2	34°06'	120°42'	2370	1067	402	5.0	0.4	34.36	7.5	0.06

[1]Bottom water characteristics derived from References 2 and 3

Table 2. Chemical Composition of Steels and Irons, Percent by Weight

Material	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source
Wrought Iron	0.02	0.06	0.13	0.01	0.13	-	-	-	-	-	2.5 Slag	NCEL
AISI 1010	0.12	0.50	0.004	0.023	0.060	-	-	-	-	-	-	NCEL
AISI 1010	0.11	0.52	0.016	0.024	0.048	-	-	-	-	-	-	NCEL
AISI 1010	-	0.34	0.01	-	0.02	0.04	0.02	-	0.03	-	-	INCO[1/]
Copper steel	-	0.40	0.01	-	0.02	0.01	0.03	-	0.28	-	-	INCO[1/]
ASTM-A36	0.24	0.70	0.011	0.027	0.055	-	-	-	-	-	-	NCEL
ASTM-A36	0.20	0.55	0.010	0.020	0.064	-	-	-	-	-	-	NCEL
ASTM-A387, D	0.06	0.49	0.013	0.021	0.24	-	2.20	1.02	-	-	-	NCEL
HSLA #1[2/]	0.18	0.86	0.014	0.023	0.28	0.05	0.64	0.18	-	-	V-0.047 B-0.0028 Ti-0.020	NCEL
HSLA #2	0.12	0.30	0.015	0.025	0.27	2.34	1.25	0.20	0.17	-	-	NCEL
HSLA #3	0.17	0.28	0.020	0.018	0.20	2.96	1.76	0.40	-	-	-	NCEL
HSLA #3	0.10	0.28	0.014	0.010	0.25	2.91	1.59	0.52	-	-	-	NCEL
HSLA #4	0.07	0.38	0.11	0.025	0.54	0.31	0.88	-	0.28	-	-	NCEL
HSLA #4	-	0.36	0.08	-	0.41	0.32	0.72	-	0.38	-	-	INCO[1/]
HSLA #5	0.14	0.78	0.020	0.025	0.23	0.74	0.56	0.42	0.22	-	V-0.35 B-0.0041	NCEL
HSLA #5	With mill scale											INCO[1/]
HSLA #6	0.26	0.13	0.007	0.008	0.01	3.07	1.43	0.97	-	-	Cb-0.07	NCEL
HSLA #7	-	0.43	0.12	-	0.13	0.54	-	-	1.0	-	-	INCO[1/]
HSLA #8	-	0.24	0.03	-	0.004	0.47	0.51	-	0.51	-	-	INCO[1/]
HSLA #9	-	0.75	0.12	-	0.55	1.00	0.70	-	0.50	-	-	INCO[1/]
HSLA #10	-	0.63	0.01	-	-	0.99	-	-	1.42	-	-	INCO[1/]
HSLA #11	-	0.69	0.08	-	-	0.50	0.26	-	0.30	-	-	INCO[1/]
Ni-Co	0.28	0.29	0.005	0.005	0.10	8.26	0.53	0.47	-	3.82	V-0.15	NCEL
18% Ni-Maraging	0.02	0.10	0.005	0.007	0.14	17.92	-	4.78	-	8.75	B-0.003 Ti-0.94 Al-0.[illegible]7	NCEL

continued

Table 2. (continued)

Material	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source
18% Ni-Maraging	0.02	0.05	0.005	0.010	0.06	18.17	-	4.85	0.10	8.13	Ti-0.35 Al-0.03	NCEL
18% Ni-Maraging	-	-	-	-	-	18.0	-	5.0	-	7.0	-	INCO[1/]
1.5% Ni	Not Recorded											INCO[1/]
3.0% Ni	Not Recorded											INCO[1/]
5.0% Ni	Not Recorded											INCO[1/]
9% Ni	Not Recorded											INCO[1/]
AISI 4340	0.43	0.73	0.013	0.014	0.27	1.77	0.82	0.24	-	-	-	NCEL
ARMCO Iron	-	0.02	-	-	-	-	-	-	-	-	-	INCO[1/]
Gray Iron, Cast	Not Recorded											INCO[1/]
Ni Iron, Cast	-	0.68	-	-	2.47	1.56	-	-	-	-	-	INCO[1/]
Ni-Cr Iron, #1, Cast	-	0.73	-	-	1.64	1.66	0.60	-	-	-	-	INCO[1/]
Ni-Cr Iron, #2, Cast	-	0.86	-	-	1.99	3.22	0.98	-	-	-	-	INCO[1/]
Ductile Iron, #1, Cast	-	0.35	-	-	2.50	0.91	-	-	-	-	-	INCO[1/]
Ductile Iron, #2, Cast	-	0.34	-	-	2.24	-	-	-	-	-	-	INCO[1/]
Si Iron, Cast	-	-	-	-	14.5	-	-	-	-	-	-	INCO[1/]
Si + Mo Iron, Cast	-	-	-	-	14.0	-	-	3.0	-	-	-	INCO[1/]
Austenitic, Type 1, Cast	-	1.4	-	-	2.05	15.8	1.79	-	6.71	-	-	INCO[1/]
Austenitic, Type 2, Cast	-	1.01	-	-	2.29	18.2	2.04	-	-	-	-	INCO[1/]
Austenitic, Type 3, Cast	-	0.6	-	-	1.15	28.4	2.87	-	-	-	-	INCO[1/]
Austenitic, Type 4, Cast	-	0.56	-	-	5.34	29.7	4.94	-	-	-	-	INCO[1/]
Austenitic, Type 4, Cast	2.13	0.79	-	-	5.60	29.98	5.02	-	0.16	-	-	NCEL
Austenitic, Type D-2, Cast	-	0.94	-	-	3.0	21.4	2.26	-	-	-	-	INCO[1/]

continued

Table 2. (continued)

Material	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source
Austenitic, Type D-2b, Cast	-	0.96	-	-	2.0	20.8	3.19	-	-	-	-	INCO 1/
Austenitic, Type D-2c, Cast	2.45	2.12	0.017	-	2.38	22.34	0.08	-	-	-	-	NCEL
Austenitic, Type D-3, Cast	-	0.5	-	-	1.83	29.8	2.70	-	-	-	-	INCO 1/
Austenitic, Hard-enable, Cast	Not Recorded											INCO 1/
Galvanized, 1.0oz	0.15, max	0.25-0.60	0.040, max	0.050 max	ASTM Spec. A526-64T, 18 gage							NCEL
Aluminized, Type 2 (1.03 oz)												NCEL
AISI Type 502	0.06	0.48	0.020	0.010	0.33	-	4.75	0.55	-	-	-	NCEL
AISI Type 502	0.06	0.5	-	-	-	0.4	5.2	0.5	-	-	-	INCO 1/

1/ Reference 18

2/ High-Strength Low-Alloy Steel

Table 3. Condition of the Steels, As Received

Alloy	Condition
Wrought Iron	As fabricated pipe
AISI C1010	Hot rolled (mill) and pickled (laboratory)
ASTM A36	Hot rolled (mill) and pickled (laboratory)
ASTM A387, D	Hot rolled (mill) and pickled (laboratory)
HSLA No. 1	Water quenched from 1650° to 1750°F and tempered at 1100° to 1275°F (mill), blast cleaned (laboratory)
HSLA No. 2	Hot rolled and pickled
HSLA No. 3	Water quenched from 1650°F and tempered at 1150° to 1200°F (mill), blast cleaned (laboratory)
HSLA No. 4	Hot rolled (mill) and pickled (laboratory)
HSLA No. 5	Water quenched from 1650° to 1750°F and tempered at 1150° to 1275°F (mill), blast cleaned (laboratory)
HSLA No. 6	Consumable electrode vacuum melt, hot rolled, annealed, cleaned and oiled
Ni-Co	Consumable electrode vacuum melt, hot rolled, annealed, cleaned and oiled
AISI 4340 (200 KSI)	Oil quenched from 1550°F, tempered for 1 hour at 750°F, blast cleaned (laboratory)
AISI 4340 (150 KSI)	Oil quenched from 1550°F, tempered for 1 hour at 1050°F, blast cleaned (laboratory)
AISI Type 502	Annealed and pickled, No. 1 sheet finish (mill).

continued

Table 3. (continued)

Alloy	Condition
18% Ni, Maraging (0.202)	Electric furnace air melt, air cast, annealed, desealed and oiled
18% Ni, Maraging (0.082)	Electric furnace air melt, air cast, annealed, desealed and oiled (mill); NCEL unwelded, aged at 900°F for 3 hours, air cooled , then welded.
18% Ni, Maraging	Electric furnace air melt, air cast, annealed, aged at 950°F for 3 hours, air cooled, as rolled surfaces
18% Ni, Maraging	Electric furnace air melt, air cast, annealed, aged at 950°F for 3 hours, air cooled, surfaces ground to RMS-125
Austenitic, Type 4 Cast Iron	As cast
Nodular austenitic, Type D-2C, Cast Iron	As cast
Galvanized 18 gage	1.0 oz/ft^2
Aluminized Type 2	Commercial quality, 1.03 oz/ft^2

Table 4. Corrosion Rates of Irons and Steels

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1]				Type of Corrosion[4]	Source
					Crevice[3]			
			W[2]	M	W	M		
Armco iron[5]	123	5640	3.1	2.4	-	-	U	INCO[6]
Armco iron[5]	403	6780	1.5	0.5[7]	-	-	U	INCO[6]
Armco iron[5]	751	5640	0.8	0.7	-	-	G	INCO[6]
Armco iron[5]	1064	5300	0.7	1.9[8]	-	-	U	INCO[6]
Armco iron[5]	197	2340	1.9	0.9	-	-	G	INCO[6]
Armco iron[5]	402	2370	1.4	1.4	-	-	G	INCO[6]
Wrought iron[9]	123	5640	2.6	-	-	-	U	NCEL
Wrought iron[9]	403	6780	1.4	1.2	-	-	U	NCEL
Wrought iron[9]	751	5640	0.9	-	-	-	U	NCEL
Wrought iron[9]	1064[10]	5300	0.6	-	-	-	U	NCEL
Wrought iron[9]	197	2340	2.0	1.2	-	-	U	NCEL
Wrought iron[9]	402	2370	1.5	1.5	-	-	G	NCEL
AISI 1010 (Plate)	90	4500	6.0	-	-	-	U	NASL[11]
AISI 1010 (Disc)	90	4500	4.5	-	-	-	U	NASL[11]
AISI 1010[5]	101	4250	4.8	-	-	-	U	NASL-INCO[12]
AISI 1010	111	5600	3.7	-	-	-	U	NRL[13]
AISI 1010	123	5640	3.0	2.2	3.0	2.2	U	NCEL
AISI 1010[5]	123	5640	2.4	1.5	-	-	U	INCO[6]
AISI 1010 (Plate)	180	4500	5.8	-	-	-	U	NASL[11]
AISI 1010 (Disc)	180	4500	7.9	-	-	-	U, C	NASL[11]
AISI 1010	403	6780	1.5	1.7	1.4	1.8	U	NCEL
AISI 1010[5]	403	6780	2.3	0.5[14]	-	-	G	INCO[6]
AISI 1010	751	5640	0.9	-	0.9	-	U	NCEL
AISI 1010[5]	751	5640	0.8	0.6	-	-	G	INCO[6]
AISI 1010	1050	5600	1.8	1.1	-	-	U	NRL[13]
AISI 1010[9]	1064	5300	0.8	-	-	-	U	NCEL

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/]				Type of Corrosion[4/]	Source
			W[2/]	M	Crevice[3/]			
					W	M		
AISI 1010	1064	5300	1.1	1.0	0.5	0.8	U	NCEL
AISI 1010[5/]	1064	5300	0.9	0.5	-	-	U	INCO[6/]
AISI 1010	197	2340	1.5	1.7	1.5	1.6	U	NCEL
AISI 1010[5/]	197	2340	1.7	0.6	-	-	G	INCO[6/]
AISI 1010	402	2370	1.2	1.1	1.2	1.4	U	NCEL
AISI 1010[5/]	402	2370	1.1	1.1	-	-	G	INCO[6/]
Copper Steel[5/]	123	5640	1.9	1.6	-	-	U	INCO[6/]
Copper Steel[5/]	403	6780	2.1	0.7	-	-	G	INCO[6/]
Copper Steel[5/]	751	5640	1.4	0.6	-	-	G	INCO[6/]
Copper Steel[5/]	1064	5300	0.5	0.4	-	-	U	INCO[6/]
Copper Steel[5/]	197	2340	2.0	0.5	-	-	G	INCO[6/]
Copper Steel[5/]	402	2370	1.1	1.2	-	-	U, G	INCO[6/]
ASTM A36	123	5640	3.1	2.4	3.0	2.1	U	NCEL
ASTM A36	403	6780	1.5	1.8	1.5	1.7	U	NCEL
ASTM A36	751	5640	0.9	-	0.9	0.7	U	NCEL
ASTM A36[9/]	1064	5300	0.6	-	-	-	U	NCEL
ASTM A36	197	2340	1.7	1.7	1.7	1.7	U	NCEL
ASTM A36	402	2370	1.3	1.5	1.3	1.4	U	NCEL
ASTM A387-D	123	5640	3.0	2.3	3.0	2.6	U	NCEL
ASTM A387-D	403	6780	2.0	1.9	1.7	2.2	U	NCEL
ASTM A387-D	751	5640	0.9	0.9	1.3	0.9	U	NCEL
ASTM A387-D	197	2340	1.8	2.0	2.1	1.8	U	NCEL
ASTM A387-D	402	2370	1.3	1.3	1.6	1.0	U	NCEL
HSLA[15/] #1	123	5640	2.9	2.2	2.7	1.9	U	NCEL
HSLA #1	403	6780	2.0	1.2	2.1	1.2	U	NCEL
HSLA #1	751	5640	0.9	-	0.6	-	U	NCEL

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1]				Type of Corrosion[4]	Source
			W[2]	M	Crevice[3]			
					W	M		
HSLA #1[9]	1064	5300	0.6	-	-	-	U	NCEL
HSLA #1	1064	5300	0.6	0.7	0.6	0.6	U	NCEL
HSLA #1	197	2340	1.4	1.4	1.3	1.4	U	NCEL
HSLA #1	402	2370	1.0	1.0	1.1	1.0	U	NCEL
HSLA #2	111	5600	4.9	-	-	-	G, P	NRL[13]
HSLA #2	123	5640	4.7	4.3	4.6	4.4	U	NCEL
HSLA #2	403	6780	2.1	2.2	2.1	2.0	U	NCEL
HSLA #2	751	5640	0.9	-	1.0	-	U	NCEL
HSLA #2	1050	5600	1.8	-	-	-	G, P	NRL[13]
HSLA #2[9]	1064	5300	0.5	-	-	-	U	NCEL
HSLA #2	197	2340	1.4	1.4	1.5	1.5	U	NCEL
HSLA #2	402	2370	1.3	1.1	1.2	1.1	U	NCEL
HSLA #3[9]	1064	5300	0.7	-	-	-	U	NCEL
HSLA #4[9]	123	5640	3.6	-	-	-	U	NCEL
HSLA #4[5]	123	5640	4.3	1.8	-	-	U, C, 9 mils	INCO[6]
HSLA #4[9]	403	6780	3.3	2.3	-	-	U	NCEL
HSLA #4[5]	403	6780	2.1	0.4	-	-	G	INCO[6]
HSLA #4[9]	761	5640	1.2	-	-	-	U	NCEL
HSLA #4[5]	751	5640	0.9	0.7	-	-	G	INCO[6]
HSLA #4[9]	1064	5300	0.3	-	-	-	U	NCEL
HSLA #4	1064	5300	1.1	-	0.7	-	U	NCEL
HSLA #4[5]	1064	5300	0.6	0.6	-	-	U	INCO[6]
HSLA #4[9]	197	2340	1.4	0.9	-	-	U	NCEL
HSLA #4[5]	197	2340	2.2	0.7	-	-	G	INCO[6]
HSLA #4[9]	402	2370	1.1	1.1	-	-	G	NCEL
HSLA #4[5]	402	2370	1.3	1.0	-	-	G	INCO[6]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/] W[2/]	Corrosion Rate, MPY[1/] M	Crevice[3/] W	Crevice[3/] M	Type of Corrosion[4/]	Source
HSLA #5	123	5640	3.1	1.6	2.1	1.1	U	NCEL
HSLA #5[5/]	123	5640	6.0	3.5	-	-	E	INCO[6/]
HSLA #5	403	6780	2.7	1.8	2.6	1.8	U	NCEL
HSLA #5[5/]	403	6780	7.4	0.2	-	-	SE, P, 3 mils	INCO[6/]
HSLA #5	751	5640	1.4	0.9	0.5	-	U	NCEL
HSLA #5[5/]	751	5640	3.1	3.2	-	-	G, SE	INCO[6/]
HSLA #5[9/]	1064	5300	0.9	-	-	-	U	NCEL
HSLA #5	1064	5300	0.7	1.0	0.8	0.9	U	NCEL
HSLA #5[5/]	1064	5300	0.9	1.0	-	-	U	INCO[6/]
HSLA #5	197	2340	1.4	1.5	1.4	1.4	U	NCEL
HSLA #5[5/]	197	2340	3.3	0.9	-	-	E, IP	INCO[6/]
HSLA #5	402	2370	1.1	1.3	1.1	1.3	U	NCEL
HSLA #5[5/]	402	2370	1.4	1.3	-	-	U, G	INCO[6/]
HSLA #6	402	2370	0.9	0.9	-	-	U	NCEL
HSLA #7[5/]	123	5640	3.5	2.1	-	-	C, 4 mils, U	INCO[6/]
HSLA #7[5/]	403	6780	1.5	0.3	-	-	G	INCO[6/]
HSLA #7[5/]	751	5640	0.8	1.3	-	-	G	INCO[6/]
HSLA #7[5/]	1064	5300	0.8	0.6	-	-	U	INCO[6/]
HSLA #7[5/]	197	2340	2.3	0.6	-	-	G	INCO[6/]
HSLA #7[5/]	402	2370	1.4	1.1	-	-	G	INCO[6/]
HSLA #8[5/]	123	5640	3.8	2.3	-	-	U	INCO[6/]
HSLA #8[5/]	403	6780	2.3	0.3	-	-	G	INCO[6/]
HSLA #8[5/]	751	5640	1.2	0.8	-	-	G	INCO[6/]
HSLA #8[5/]	1064	5300	0.7	0.5	-	-	U	INCO[6/]
HSLA #8[5/]	197	2340	1.9	0.7	-	-	G	INCO[6/]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1]		Crevice[3]		Type of Corrosion[4]	Source
			W[2]	M	W	M		
HSLA #9[5]	123	5640	4.3	2.1	-	-	C, 10 & 4 mils	INCO[6]
HSLA #9[5]	403	6780	2.5	0.3	-	-	G	INCO[6]
HSLA #9[5]	751	5640	1.4	1.0	-	-	G	INCO[6]
HSLA #9[5]	1064	5300	0.6	0.5	-	-	U	INCO[6]
HSLA #9[5]	197	2340	1.6	0.6	-	-	G	INCO[6]
HSLA #10[5]	123	5640	4.1	2.5	-	-	C, 9 mils, U	INCO[6]
HSLA #10[5]	403	6780	1.8	0.5	-	-	G	INCO[6]
HSLA #10[5]	751	5640	0.9	1.1	-	-	G	INCO[6]
HSLA #10[5]	1064	5300	0.9	0.6	-	-	U	INCO[6]
HSLA #10[5]	197	2340	2.1	0.8	-	-	G	INCO[6]
HSLA $10[5]	402	2370	1.5	1.2	-	-	G	INCO[6]
HSLA #11[5]	123	5640	3.4	1.7	-	-	U	INCO[6]
HSLA #11[5]	403	6780	2.4	0.4	-	-	G	INCO[6]
HSLA #11[5]	751	5640	1.2	0.8	-	-	G	INCO[6]
HSLA #11[5]	1064	5300	0.7	0.5	-	-	U	INCO[6]
HSLA #11[5]	197	2340	1.8	0.6	-	-	G	INCO[6]
18 Ni Maraging	123	5640	3.6	-	-	-	U	NAEC[17]
18 Ni Maraging[5]	402	2370	1.3	0.9	-	-	G	NCEL
18 Ni Maraging[5]	402	2370	1.5	0.8	-	-	G	INCO[6]
18 Ni Maraging (As Rolled)	402	2370	1.4	1.3	-	-	G	NCEL
18 Ni Maraging (Machined)	402	2370	1.3	1.2	-	-	G	NCEL
18 Ni Maraging[9]	402	2370	3.5	2.6	-	-	G	NCEL[16]
18 Ni Maraging[9] Welded	402	2370	2.8	1.7	-	-	G	NCEL[16]
Ni-Co	402	2370	1.7	1.4	-	-	G	NCEL
1.5 Ni steel[5]	123	5640	3.5	2.7	-	-	U	INCO[6]
1.5 Ni steel[5]	403	6780	1.7	0.8	-	-	G	INCO[6]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/]				Type of Corrosion[4/]	Source
			W[2/]	M	Crevice[3/]			
					W	M		
1.5 Ni steel[5/]	751	5640	1.0	0.5	-	-	G	INCO[6/]
1.5 Ni steel[5/]	1064	5300	0.7	0.7	-	-	U	INCO[6/]
1.5 Ni steel[5/]	197	2340	1.9	0.5	-	-	U	INCO[6/]
1.5 Ni steel[5/]	402	2370	1.5	1.2	-	-	U	INCO[6/]
3 Ni steel[5/]	123	5640	3.4	3.0	-	-	U	INCO[6/]
3 Ni steel[5/]	403	6780	1.9	0.4	-	-	C, 2 mils, G	INCO[6/]
3 Ni steel[5/]	751	5640	0.9	0.9	-	-	G	INCO[6/]
3 Ni steel[5/]	1064	5300	0.9	0.6	-	-	U	INCO[6/]
3 Ni steel[5/]	197	2340	1.7	0.4	-	-	G	INCO[6/]
3 Ni steel[5/]	402	2370	1.3	1.0	-	-	G	INCO[6/]
5 Ni steel[5/]	123	5640	2.8	2.8	-	-	U	INCO[6/]
5 Ni steel[5/]	403	6780	2.8	0.4	-	-	C, 6 mils, G	INCO[6/]
5 Ni steel[5/]	751	5640	1.1	0.8	-	-	G	INCO[6/]
5 Ni steel[5/]	1064	5300	0.7	0.5	-	-	U	INCO[6/]
5 Ni steel[5/]	197	2340	1.7	0.4	-	-	G	INCO[6/]
5 Ni steel[5/]	402	2370	1.3	1.1	-	-	U	INCO[6/]
9 Ni steel[5/]	123	5640	5.6	5.6	-	-	U	INCO[6/]
9 Ni steel[5/]	403	6780	2.9	0.5	-	-	C, 9 mils, G	INCO[6/]
9 Ni steel[5/]	751	5640	1.1	4.5	-	-	G	INCO[6/]
9 Ni steel[5/]	1064	5300	4.6	1.2	-	-	U	INCO[6/]
9 Ni steel[5/]	197	2340	1.9	0.4	-	-	G	INCO[6/]
9 Ni steel[5/]	402	2370	1.6	1.3	-	-	G	INCO[6/]
AISI 4130 (100 KSI)	123	5640	2.3	-	-	-	U	NAEC[17/]
AISI 4130 (160 KSI)	123	5640	3.1	-	-	-	U	NAEC[17/]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/] W[2/]	Corrosion Rate, MPY[1/] M	Crevice[3/] W	Crevice[3/] M	Type of Corrosion[4/]	Source
AISI 4340 (150 KSI)[9/]	123	5640	2.7	-	-	-	U	NCEL
AISI 4340 (150 KSI)[9/]	403	6780	2.2	1.7	-	-	U	NCEL
AISI 4340 (150 KSI)	403	6780	2.2	1.5	2.5	1.6	U	NCEL
AISI 4340 (150 KSI)[9/]	751	5640	0.8	-	-	-	U	NCEL
AISI 4340 (150 KSI)[9/]	197	2340	1.9	1.3	-	-	U	NCEL
AISI 4340 (150 KSI)	197	2340	1.6	1.8	1.6	1.8	U	NCEL
AISI 4340 (150 KSI)	402	2370	1.2	1.3	1.3	1.4	U	NCEL
AISI 4340 (200 KSI)[9/]	123	5640	2.8	-	-	-	U	NCEL
AISI 4340 (200 KSI)[9/]	403	6780	2.0	1.9	-	-	U	NCEL
AISI 4340 (200 KSI)	403	6780	2.0	1.8	2.2	1.9	U	NCEL
AISI 4340 (200 KSI)[9/]	751	5640	0.9	-	-	-	U	NCEL
AISI 4340 (200 KSI)[9/]	197	2340	1.4	1.4	-	-	U	NCEL
AISI 4340 (200 KSI)	197	2340	2.1	2.2	2.0	2.2	U	NCEL
AISI 4340 (200 KSI)	402	2370	1.4	1.4	1.4	1.4	U	NCEL
AISI Type 502	123	5640	5.9	4.3	3.5	3.5	P, C to 21 mils	NCEL
AISI Type 502[5/]	123	5640	4.3	4.6	-	-	P, 12 & 9 mils	INCO[6/]
AISI Type 502	403	6780	2.3	2.6	3.4	2.5	(E, P to 24 mils (C to 22 mils	NCEL
AISI Type 502[5/]	403	6780	13.2	0.4	-	-	P, C to 35 mils, G	INCO[6/]
AISI Type 502	751	5640	2.8	-	3.1	-	E, C to 50 mils, P to 36 mils	NCEL
AISI Type 502[5/]	751	5640	4.4	2.5	-	-	C to PR	INCO[6/]
AISI Type 502[9/]	1064	5300	2.6	-	-	-	C	NCEL
AISI Type 502	1064	5300	1.9	1.7	1.6	1.8	P, C	NCEL
AISI Type 502[5/]	1064	5300	3.0	1.1	-	-	C to PR	INCO[6/]
AISI Type 502	197	2340	1.4	1.2	0.6	1.0	P, C to 23 mils	NCEL
AISI Type 502[5/]	197	2340	3.1	0.2	-	-	E, C to 20 mils	INCO[6/]
AISI Type 502	402	2370	0.8	0.6	1.7	0.5	I, C to 16 mils	NCEL
AISI Type 502[5/]	402	2370	3.1	0.1	-	-	P, C to PR	INCO[6/]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/]				Type of Corrosion[4/]	Source
			W[2/]	M	Crevice[3/]			
					W	M		
Gray cast iron[5/]	123	5640	4.2	3.0	-	-	U	INCO[6/]
Gray cast iron[5/]	403	6780	1.8	1.3	-	-	U	INCO[6/]
Gray cast iron[5/]	751	5640	1.2	1.0	-	-	G	INCO[6/]
Gray cast iron[5/]	1064	5300	0.8	0.5	-	-	U	INCO[6/]
Gray cast iron[5/]	197	2340	2.0	0.3	-	-	G	INCO[6/]
Gray cast iron[5/]	402	2370	1.7	2.0	-	-	U	INCO[6/]
Ni Cast iron[5/]	123	5640	4.4	3.4	-	-	U	INCO[6/]
Ni Cast iron[5/]	403	6780	2.9	1.5	-	-	U, M	INCO[6/]
Ni Cast iron[5/]	751	5640	1.4	1.1	-	-	G	INCO[6/]
Ni Cast iron[5/]	1064	5300	0.9	1.5	-	-	G	INCO[6/]
Ni Cast iron[5/]	197	2340	2.2	0.3	-	-	G	INCO[6/]
Ni Cast iron[5/]	402	2370	1.5	1.5	-	-	U	INCO[6/]
Ni-Cr cast iron #1[5/]	123	5640	4.3	3.3	-	-	U	INCO[6/]
Ni-Cr cast iron #1[5/]	403	6780	1.7	1.2	-	-	U	INCO[6/]
Ni-Cr cast iron #1[5/]	751	5640	1.3	0.9	-	-	G	INCO[6/]
Ni-Cr cast iron #1[5/]	1064	5300	0.8	0.7	-	-	U	INCO[6/]
Ni-Cr cast iron #1[5/]	197	2340	1.9	0.3	-	-	G	INCO[6/]
Ni-Cr cast iron #1[5/]	402	2370	1.8	1.4	-	-	U	INCO[6/]
Ni-Cr cast iron #2[5/]	123	5640	4.3	3.7	-	-	U	INCO[6/]
Ni-Cr cast iron #2[5/]	403	6780	1.8	1.4	-	-	U	INCO[6/]
Ni-Cr cast iron #2[5/]	751	5640	1.3	1.1	-	-	G	INCO[6/]
Ni-Cr cast iron #2[5/]	1064	5300	0.7	0.7	-	-	U	INCO[6/]
Ni-Cr cast iron #2[5/]	197	2340	1.9	0.3	-	-	G	INCO[6/]
Ni-Cr cast iron #2[5/]	402	2370	1.8	1.1	-	-	U	INCO[6/]
Ductile cast iron #1[5/]	123	5640	3.1	3.0	-	-	U	INCO[6/]
Ductile cast iron #1[5/]	403	6780	3.4	1.0	-	-	G	INCO[6/]
Ductile cast iron #1[5/]	751	5640	1.0	0.9	-	-	G	INCO[6/]
Ductile cast iron #1[5/]	1064	5300	0.6	0.7	-	-	U	INCO[6/]
Ductile cast iron #1[5/]	197	2340	1.9	0.7	-	-	G	INCO[6/]
Ductile cast iron #1[5/]	402	2370	1.9	1.7	-	-	U	INCO[6/]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/]				Type of Corrosion[4/]	Source
			W[2/]	M	Crevice[3/] W	Crevice[3/] M		
Ductile cast iron #2[5/]	123	5640	3.9	2.9	-	-	U	INCO[6/]
Ductile cast iron #2[5/]	403	6780	2.9	0.9	-	-	G, M	INCO[6/]
Ductile cast iron #2[5/]	751	5640	1.0	0.8	-	-	G	INCO[6/]
Ductile cast iron #2[5/]	1064	5300	0.8	0.6	-	-	U	INCO[6/]
Ductile cast iron #2[5/]	197	2340	2.3	0.5	-	-	G	INCO[6/]
Ductile cast iron #2[5/]	402	2370	1.8	1.4	-	-	U	INCO[6/]
Silicon cast iron[5/]	123	5640	< 0.1	< 0.1	-	-	NC	INCO[6/]
Silicon cast iron[5/]	403	6780	< 0.1	< 0.1	-	-	NC	INCO[6/]
Silicon cast iron[5/]	751	5640	< 0.1	< 0.1	-	-	NC	INCO[6/]
Silicon cast iron[5/]	1064	5300	< 0.1	< 0.1	-	-	NC	INCO[6/]
Silicon cast iron[5/]	197	2340	< 0.1	< 0.1	-	-	NC	INCO[6/]
Silicon cast iron[5/]	402	2370	< 0.1	< 0.1	-	-	NC	INCO[6/]
Si-Mo cast iron[5/]	123	5640	< 0.1	< 0.1	-	-	NC	INCO[6/]
Si-Mo cast iron[5/]	403	6780	< 0.1	< 0.1	-	-	NC	INCO[6/]
Si-Mo cast iron[5/]	751	5640	< 0.1	< 0.1	-	-	NC	INCO[6/]
Si-Mo cast iron[5/]	1064	5300	< 0.1	< 0.1	-	-	NC	INCO[6/]
Si-Mo cast iron[5/]	197	2340	< 0.1	< 0.1	-	-	NC	INCO[6/]
Si-Mo cast iron[5/]	402	2370	< 0.1	< 0.1	-	-	NC	INCO[6/]
Ni-Resist Type 1[5/]	123	5640	2.4	2.4	-	-	G	INCO[6/]
Ni-Resist Type 1[5/]	403	6780	1.0	0.2	-	-	U	INCO[6/]
Ni-Resist, Type 1[5/]	751	5640	0.5	0.8	-	-	G	INCO[6/]
Ni-Resist, Type 1[5/]	1064	5300	0.5	0.6	-	-	U	INCO[6/]
Ni-Resist, Type 1[5/]	197	2340	1.8	1.1	-	-	G	INCO[6/]
Ni-Resist, Type 1[5/]	402	2370	1.5	0.6	-	-	U	INCO[6/]
Ni-Resist, Type 2[5/]	123	5640	2.4	2.2	-	-	G	INCO[6/]
Ni-Resist, Type 2[5/]	403	6780	2.2	0.2	-	-	U	INCO[6/]
Ni-Resist, Type 2[5/]	751	5640	1.5	1.6	-	-	G	INCO[6/]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1/]				Type of Corrosion[4/]	Source
			W[2/]	M	Crevice[3/]			
					W	M		
Ni-Resist, Type 2[5/]	1064	5300	1.4	1.0	-	-	G	INCO[6/]
Ni-Resist, Type 2[5/]	197	2340	1.3	1.1	-	-	G	INCO[6/]
Ni-Resist, Type 2[5/]	402	2370	1.1	0.7	-	-	U	INCO[6/]
Ni-Resist, Type 3[5/]	123	5640	1.9	1.7	-	-	G	INCO[6/]
Ni-Resist, Type 3[5/]	403	6780	1.8	<0.1	-	-	U	INCO[6/]
Ni-Resist, Type 3[5/]	751	5640	1.9	1.9	-	-	G	INCO[6/]
Ni-Resist, Type 3[5/]	1064	5300	1.2	0.8	-	-	U	INCO[6/]
Ni-Resist, Type 3[5/]	197	2340	0.8	0.7	-	-	G	INCO[6/]
Ni-Resist, Type 3[5/]	402	2370	0.6	0.7	-	-	U	INCO[6/]
Ni-Resist, Type 4[5/]	123	5640	1.8	1.6	-	-	G	INCO[6/]
Ni-Resist, Type 4[5/]	403	6780	2.0	1.3	-	-	U	INCO[6/]
Ni-Resist, Type 4[5/]	751	5640	1.2	1.5	-	-	G	INCO[6/]
Ni-Resist, Type 4[5/]	1064	5300	0.9	0.4	-	-	U	INCO[6/]
Ni-Resist, Type 4[5/]	197	2340	0.8	0.4	-	-	G	INCO[6/]
Ni-Resist, Type 4[9/]	402	2370	0.9	0.7	-	-	G	NCEL
Ni-Resist, Type 4[5/]	402	2370	0.8	0.3	-	-	U	INCO[6/]
Ni-Resist, Type D-2[5/]	123	5640	2.6	2.4	-	-	G	INCO[6/]
Ni-Resist, Type D-2[5/]	403	6780	1.2	0.2	-	-	U	INCO[6/]
Ni-Resist, Type D-2[5/]	751	5640	1.3	1.5	-	-	G	INCO[6/]
Ni-Resist, Type D-2[5/]	1064	5300	1.1	0.4	-	-	U	INCO[6/]
Ni-Resist, Type D-2[5/]	197	2340	1.2	0.2	-	-	G	INCO[6/]
Ni-Resist, Type D-2[5/]	402	2370	1.1	0.5	-	-	U	INCO[6/]
Ni-Resist, Type D-2b[5/]	123	5640	2.1	2.0	-	-	G	INCO[6/]
Ni-Resist, Type D-2b[5/]	403	6780	1.6	0.1	-	-	U	INCO[6/]
Ni-Resist, Type D-2b[5/]	751	5640	1.2	1.3	-	-	G	INCO[6/]
Ni-Resist, Type D-2b[5/]	1064	5300	1.0	0.4	-	-	G	INCO[6/]
Ni-Resist, Type D-2b[5/]	197	2340	1.4	0.1	-	-	G	INCO[6/]
Ni-Resist, Type D-2b[5/]	402	2370	0.9	0.6	-	-	U	INCO[6/]

continued

Table 4. (continued)

Alloy	Exposure, Days	Depth, Feet	Corrosion Rate, MPY[1]				Type of Corrosion[4]	Source
			W[2]	M	Crevice[3]			
					W	M		
Ni-Resist, Type D-2c[9]	402	2370	1.8	1.2	-	-	U	INCO[6]
Ni-Resist, Type D-3[5]	123	5640	1.9	2.2	-	-	G	INCO[6]
Ni-Resist, Type D-3[5]	403	6780	2.7	0.4	-	-	G	INCO[6]
Ni-Resist, Type D-3[5]	751	5640	2.1	1.9	-	-	G	INCO[6]
Ni-Resist, Type D-3[5]	1064	5300	1.2	0.7	-	-	U	INCO[6]
Ni-Resist, Type D-3[5]	197	2340	0.9	0.2	-	-	G	INCO[6]
Ni-Resist, Type D-3[5]	402	2370	0.7	0.5	-	-	U	INCO[6]
Ni-Resist, hardenable[5]	123	5640	2.5	2.8	-	-	G	INCO[6]
Ni-Resist, hardenable[5]	403	6780	1.1	0.4	-	-	U	INCO[6]
Ni-Resist, hardenable[5]	751	5640	0.7	0.7	-	-	G	INCO[6]
Ni-Resist, hardenable[5]	1064	5300	0.6	0.7	-	-	U	INCO[6]
Ni-Resist, hardenable[5]	197	2340	2.8	0.1	-	-	G	INCO[6]
Ni-Resist, hardenable[5]	402	2370	1.8	0.5	-	-	U	INCO[6]
Galvanized steel (1.0 oz)	402	2370	0.9	0.4	-	-	G	NCEL
Aluminized steel (1.0 oz)	402	2370	0.0[18]	0.0[19]	-	-	G	NCEL

Footnotes:

1. MPY = mils penetration per year calculated from weight losses.
2. W = specimens exposed on sides of structure in the sea water.
   M = specimens exposed in the base of the structure, partially embedded in the bottom sediment.
3. An intentional crevice was formed by bolting a 1 inch square piece of the same alloy to a 6 x 12 inch specimen with a nylon bolt and nut.

continued

Footnotes (cont'd):

4. Abbreviations signify the following types of corrosion:
   U = Uniform
   G = General
   C = Crevice
   P = Pitting
   PR = Perforation
   XF = Exfoliation
   T = Tunnel
   E = Edge
   IG = Intergranular
   SCC = Stress Corrosion Cracking
   DZ = Dezincification
   DA = Dealuminification
   S = Severe
   I = Incipient
   M = Corroded at mud line
   NC = No visible corrosion
5. Disc specimens, approximately 2 inch diameter.
6. Reference 18.
7. Corrosion accelerated below mud line.
8. Crater corrosion to 12 mils.
9. Specimen size 1 x 6 inches, all others except (5), 6 x 12 inches.
10. Reference 34.
11. Reference 22
12. Reference 23
13. Reference 21
14. Crevice corrosion 2 mils at mud line.
15. HSLA = high strength low alloy constructional steels
16. Heavy, grey-black tight rust, heat treated 900°F, 3 hours and air cooled.
17. Reference 19
18. No rusting, 78% of Al coating remaining.
19. No rusting, 60% of Al coating remaining.

Table 5. Environmental Variables

Variable	Harbor Island, N. C. Surface	Pacific Ocean 5,500 Feet
Current	variable, low	0.03 knot
pH	8.1	7.6
Pressure	0	2475 psi
Temperature	19°C	2.4°C
Oxygen	5.2 ml/l	1.4 ml/l

Table 6. Stress Corrosion Tests

Alloy	Stress, KSI	% Y.S.	Exposure, Days	Depth, ft.	Number of Specimens	Number Failed
AISI 4340 (150 KSI)	46.1	35	123	5640	3	0
	46.1	35	403	6780	2	0
	46.1	35	751	5640	3	0
	46.1	35	197	2340	3	0
	65.9	50	123	5640	3	0
	65.9	50	403	6780	2	0
	65.9	50	751	5640	3	0
	65.9	50	197	2340	3	0
	65.9	50	402	2370	3	0
	98.9	75	123	5640	3	0
	98.9	75	403	6780	2	0
	98.9	75	751	5640	3	0
	98.9	75	197	2340	3	0
	98.9	75	402	2370	3	0
AISI 4340 (200 KSI)	64.7	35	123	5640	3	0
	64.7	35	403	6780	2	0
	64.7	35	751	5640	3	0
	64.7	35	197	2340	3	0
	92.5	50	123	5640	3	0
	92.5	50	403	6780	2	0
	92.5	50	751	5640	3	0
	92.5	50	197	2340	3	0
	92.5	50	402	2370	3	0
	138.7	75	123	5640	3	0
	138.7	75	403	6780	2	0
	138.7	75	751	5640	3	0
	138.7	75	197	2340	3	0
	138.7	75	402	2370	3	0
HSLA No. 1	38.4	35	197	2340	3	0
	54.8	50	197	2340	3	0
	54.8	50	402	2370	3	0
	82.3	75	197	2340	3	0
	82.3	75	402	2370	3	0
HSLA No. 5	41.4	35	197	2340	3	0
	59.1	50	197	2340	3	0
	59.1	50	402	2370	3	0
	88.7	75	197	2340	3	0
	88.7	75	402	2370	3	0

continued

Table 6. Stress Corrosion Tests (Cont'd)

Alloy	Stress, KSI	% Y.S.	Exposure, Days	Depth, Ft.	Number of Specimens	Number Failed
AISI Type 502	17.8	50	197	2340	3	0
	17.8	50	402	2370	3	0
	26.7	75	197	2340	3	0
	26.7	75	402	2370	3	0
ASTM A387, Grade D	24.3	50	402	2370	3	0
	36.5	75	402	2370	3	0
ASTM A36	20.2	50	402	2370	3	0
	30.2	75	402	2370	3	0
18% Ni Maraging	109.0	35	402	2370	3	0
	155.7	50	402	2370	3	0
	233.5	75	402	2370	3	0
18% Ni Maraging Welded	109.0	35	402	2370	3	0
	155.7	50	402	2370	3	0
	233.5	75	402	2370	3	0

Table 7. Percent Change in Mechanical Properties of Irons and Steels Due to Corrosion

ALLOY	ORIGINAL PROPERTIES		PERCENT CHANGE					
			DEPTH, 5,500 FEET				DEPTH, 2,350 FEET	
			Days				Days	
			123	403	751	1064	197	402
Wrought Iron	TS,KSI	47.0[1]	-	+ 4.6	+ 5.7	+ 6.2	-	+ 1.9
	YS,KSI	29.9[1]	-	+ 1.7	- 0.1	+ 3.3	-	- 25.1
	EL,%	15.0[1]	-	+118.1	+153.5	+113.0	-	+ 26.0
AISI 1010	TS,KSI	54.1	- 0.9	+ 1.1	+ 0.2	+ 5.8	+ 2.1	- 1.8
	YS,KSI	36.3	- 0.3	+ 5.7	+ 3.3	+ 7.5	+ 3.7	- 4.3
	EL,%	42.3	+ 1.2	- 8.2	- 3.1	- 4.9	- 4.3	- 2.6
ASTM A36	TS,KSI	65.7	- 1.0	+ 1.9	+ 1.0	+ 4.2	+ 1.8	+ 0.8
	YS,KSI	39.2	+ 1.6	+ 4.2	+ 6.4	+ 3.9	+ 4.1	- 1.6
	EL,%	39.0	+ 8.7	- 11.0	- 10.5	+ 13.5	- 1.3	- 4.2
ASTM A387-D	TS,KSI	76.3	+ 3.3	+ 6.3	+ 7.2	-	+ 4.0	+ 3.4
	YS,KSI	48.6	+ 3.9	+ 6.3	+ 7.4	-	- 1.5	+ 5.9
	EL,%	31.5	- 5.4	- 16.0	- 16.7	-	- 10.4	- 10.0
HSLA No.1	TS,KSI	121.4	+ 0.2	+ 2.5	+ 2.2	+ 2.4	+ 1.9	+ 1.1
	YS,KSI	109.7	+ 0.7	+ 2.6	+ 3.8	+ 2.7	+ 1.6	- 0.5
	EL,KSI	12.2	+ 41.8	+ 32.0	+ 31.1	+ 32.0	+ 39.3	+ 29.9
HSLA No.2	TS,KSI	100.1	+ 1.3	+ 4.3	+ 6.0	+ 6.3	+ 3.5	+ 2.3
	YS,KSI	88.9	- 2.0	- 1.8	+ 3.6	+ 3.6	+ 2.2	- 3.1
	EL,%	27.7	- 12.3	- 12.1	- 3.2	+ 41.9	- 8.5	- 11.0
HSLA No. 3	TS,KSI	106.7	-	-	-	+ 9.6	-	-
	YS,KSI	87.5	-	-	-	+ 4.0	-	-
	EL,%	30.0	-	-	-	+ 33.3	-	-

continued

Table 7. Percent Change in Mechanical Properties of Irons and Steels Due to Corrosion (continued)

ALLOY	ORIGINAL PROPERTIES		PERCENT CHANGE					
			DEPTH, 5,500 FEET				DEPTH, 2,350 FEET	
			Days				Days	
			123	402	751	1064	197	402
HSLA No. 4	TS,KSI	70.2	+ 4.8	+ 3.9	+ 4.0	+ 4.6	+ 5.5	+ 3.2
	YS,KSI	52.4	+ 7.4	+ 4.0	+ 6.5	+ 5.5	+ 7.8	- 2.1
	EL,%	32.3	+ 23.8	+ 39.6	+ 17.6	+ 19.5	+ 35.5	- 33.0
HSLA No. 5	TS,KSI	125.4	+ 1.0	+ 4.1	+ 6.3	+ 5.7	+ 2.3	+ 3.3
	YS,KSI	117.9	+ 1.5	+ 5.3	+ 4.6	+ 5.7	+ 2.3	+ 4.1
	EL,%	15.7	- 1.3	- 10.9	- 6.1	- 1.7	+ 1.6	- 2.9
HSLA No. 6	TS,KSI	131.4	-	-	-	-	-	+ 2.0
	YS,KSI	116.8	-	-	-	-	-	- 1.2
	EL,%	16.0	-	-	-	-	-	- 10.0
AISI 4350 (200 KSI)	TS,KSI	200.9	+ 4.4	+ 4.1	+ 2.6	-	+ 3.1	-
	YS,KSI	184.9	+ 4.7	+ 3.3	+ 9.7	-	+ 5.4	-
	EL,%	7.7	+ 42.9	+ 25.4	+ 29.9	-	+ 49.4	-
AISI 4340 (200 KSI)	TS,KSI	209.0	-	+ 1.2	-	-	- 2.1	- 1.7
	YS,KSI	189.6	-	+ 0.9	-	-	- 0.8	- 0.4
	EL,%	8.0	-	- 1.9	-	-	+ 10.7	+ 3.1
AISI 4340 (150 KSI)	TS,KSI	143.1	+ 3.4	- 1.0	+ 3.0	-	+ 4.5	-
	YS,KSI	131.8	+ 3.9	- 3.0	+ 2.7	-	+ 3.9	-
	EL,%	13.3	+ 27.8	+ 26.5	+ 27.8	-	+ 29.0	-
AISI 4340 (150 KSI)	TS,KSI	147.4	-	- 0.1	-	-	+ 0.1	- 2.4
	YS,KSI	135.8	-	- 1.2	-	-	- 0.4	- 3.4
	EL,%	14.0	-	- 5.7	-	-	- 2.5	- 5.0

continued

Table 7. Percent Change in Mechanical Properties of Irons and Steels Due to Corrosion (continued)

ALLOY	ORIGINAL PROPERTIES		PERCENT CHANGE					
			DEPTH, 5,500 FEET				DEPTH, 2,350 FEET	
			Days				Days	
			123	403	751	1064	197	402
18% Ni Maraging	TS,KSI	320.7	-	-	-	-	-	- 6.1
	YS,KSI	315.4	-	-	-	-	-	-
	EL,%	2.5	-	-	-	-	-	- 16.0
18% Ni Maraging, Welded	TS,KSI	169.6	-	-	-	-	-	- 6.2
	YS,KSI	150.7	-	-	-	-	-	- 1.1
	EL,%	8.3	-	-	-	-	-	- 51.2
18% Ni Maraging, Machined, RMS 125	TS,KSI	253.8	-	-	-	-	-	+ 6.2
	YS,KSI	236.1	-	-	-	-	-	+ 2.0
	EL,%	6.8	-	-	-	-	-	+ 16.2
18% Ni Maraging as rolled	TS,KSI	251.6	-	-	-	-	-	+ 6.8
	YS,KSI	239.0	-	-	-	-	-	+ 8.1
	EL,%	7.0	-	-	-	-	-	+ 4.3
Ni-Co	TS,KSI	168.5	-	-	-	-	-	+ 0.3
	YS,KSI	118.1	-	-	-	-	-	- 6.4
	EL,%	13.5	-	-	-	-	-	+ 8.1
Ni-Resist No. 4	TS,KSI	22.8	-	-	-	-	-	- 3.5
	YS,KSI	20.1	-	-	-	-	-	- 7.5
	EL,%	2.3	-	-	-	-	-	- 34.8
Ni-Resist D-2C	TS,KSI	46.8	-	-	-	-	-	- 38.2
	YS,KSI	41.7	-	-	-	-	-	- 56.1
	EL,%	4.7	-	-	-	-	-	- 36.2

continued

Table 7. Percent Change in Mechanical Properties of Irons and Steels Due to Corrosion (continued)

ALLOY	ORIGINAL PROPERTIES		PERCENT CHANGE					
			DEPTH, 5,500 FEET				DEPTH, 2,350 FEET	
			Days				Days	
			123	403	751	1064	197	402
AISI Type 502	TS, KSI	59.2	- 2.0	- 4.9	- 8.2	- 3.0	- 1.1	- 0.8
	YS, KSI	35.7	+ 5.3	+ 1.4	+ 5.6	+ 3.4	- 4.1	+ 3.5
	EL, %	33.2	- 33.6	- 16.5	- 38.3	- 37.8	- 2.3	- 13.4
Galvanized, 1.0 oz. per sq. ft.	TS, KSI	49.2	-	-	-	-	-	+ 3.1
	YS, KSI	39.8	-	-	-	-	-	+ 0.4
	EL, %	37.8	-	-	-	-	-	- 6.1
Aluminized, 1.0 oz. per sq. ft.	TS, KSI	51.4	-	-	-	-	-	- 2.3
	YS, KSI	38.2	-	-	-	-	-	- 7.0
	EL, %	27.8	-	-	-	-	-	+ 3.4

1/ Nominal Published Values

Table 8. Effect of Corrosion on Breaking Strengths of Anchor Chains

Designation	Condition	Size, Inch	Exposure		Breaking Load, lb.		Remarks
			Days	Depth	Original	Final	
Dilok	Degreased	0.75	123	5640	59,000	58,500	Thin film flaky rust, broke at bottom of socket
Dilok	Degreased	0.75	403	6780	59,000	64,500	Thin film flaky rust, broke at bottom of socket
Dilok	Degreased	0.75	751	5640	59,000	71,000	Thin film flaky rust, broke at bottom of socket
Dilok	Degreased	0.75	197	2340	59,000	76,500	Thin film flaky rust, broke at end of link
Welded Stud Link	Degreased	0.75	123	5640	57,500	61,500	Thin film flaky rust, broke at end of link
Welded Stud Link	Degreased	0.75	403	6780	57,500	59,500	Thin film flaky rust, broke at end of link
Welded Stud Link	Degreased	0.75	751	5640	57,500	59,500	Thin film flaky rust, broke at end of link
Welded Stud Link	Degreased	0.75	197	2340	57,500	61,000	Thin film flaky rust, broke at end of link

Table 9. Effect of Corrosion on Breaking Strengths of Unstressed Wire Ropes

Designation	Condition	Diameter, Inch	Breaking Load, lb				Remarks
			Original	123 Days, 5640 Feet	197 Days, 2340 Feet	403 Days, 6780 Feet	
Plow Steel	Lubricated, 7 x 19	0.875	49,600 1/	48,200	-	-	Rust on outside surfaces - inside bright - 45° and cup and cone fractures
Plow Steel	Degreased, 7 x 19	0.875	49,600 1/	48,200	-	-	Rust on outside surfaces - inside, few bright spots - 45° and cup and cone fractures
Plow Steel	Degreased, covered with 10 mil polyethylene tape, 7x19	0.875	49,600 1/	48,900	-	-	Rust at edges and underneath tape for about 3 feet - inside, 50 percent bright - 45° and cup and cone fractures
Galvanized aircraft cable	Lubricated, 7 x 7	0.094	1,100	-	1,000	1,100	Outside, 100% rust - inside, gray - cup and cone fracture
Galvanized aircraft cable	Lubricated, 7 x 19	0.125	2,000	-	1,800	1,000	Outside, 100% rust - inside gray - cup and cone fracture
Galvanized aircraft cable	Lubricated, 7 x 19	0.187	3,500	-	3,700	4,000	Outside, dark gray to black-inside, gray - 45° and cup and cone fractures
Galvanized aircraft cable	Lubricated, 7 x 19	0.250	6,100	-	6,200	5,900	Outside, dark gray to black-inside, gray - 45° and cup and cone fractures
Galvanized, ASTM-A 475	Class A coating, 0.50 oz. Zn, 1 x 7	0.187	2,600	-	2,500	2,600	Outside, 90% rust - inside gray - cup and cone fracture
Galvanized, ASTM-A 475	Class A coating, 0.85 oz. Zn, 1 x 7	0.250	5,900	-	5,300	4,600	Outside, yellow - inside, gray-cup and cone fracture
Stainless steel	Lubricated, 7 x 7	0.094	800	-	800	80	Outside, few rust spots - inside, many wires corroded through - fractures at corrosion pits

continued

Table 9. Effect of Corrosion on Breaking Strengths of Unstressed Wire Ropes (cont'd)

Designation	Condition	Diameter, Inch	Breaking Load, lb				Remarks
			Original	123 Days, 5640 Feet	197 Days, 2340 Feet	403 Days, 6780 Feet	
Stainless steel	Lubricated, 7 x 19	0.125	1,600	-	1,800	220	Outside, few rust stains - inside, many pits on wires, crevice corrosion - fractures at pits
Stainless steel	Lubricated, 7 x 19	0.187	2,700	-	2,800	85	Outside, many rust stains - many broken wires both external and internal - fractures at rusted areas
Stainless steel	Lubricated, 7 x 19	0.250	5,100	-	5,100	5,000	Outside, few yellow stains - inside, metallic lustre - cup and cone fracture
Stainless steel	Lubricated, 7 x 19	0.313	7,100	-	7,000	7,700	Outside few rust stains - inside, metallic lustre - 45° and cup and cone fractures
Stainless steel	Lubricated, 7 x 19	0.375	11,900	-	11,600	11,700	Outside, few rust stains - inside, few rust spots - 45° and cup and cone fractures
						402 Days 2370 Feet	
90Cu-10Ni Clad Type 304 Stainless Steel	1 x 37 x 7, coating 0.0003 inch thick	0.313	-	-	-	-	Outside, light film rust - inside, brown, uncorroded
90Cu-10Ni Clad Type 304 Stainless steel	7 x 7, coating 0.0006-0.0008 inch thick	0.187	3,280	-	-	3,300	Outside, green - inside, brown, uncorroded

continued

Table 9. Effect of Corrosion on Breaking Strengths of Unstressed Wire Ropes (cont'd)

Designation	Condition	Dia., Inch	Breaking Load, lb				Remarks
			Original	123 Days, 5640 Feet	197 Days, 2340 Feet	402 Days 2370 Feet	
Aluminized improved plow steel	7 x 7, coating 0.0006 inch thick	0.187	3,860	-	-	3,460	Outside, white corrosion products with light rust stains - inside, dull gray
Aluminized improved plow steel	1 x 19, coating 0.0006 inch thick	0.250	7,860	-	-	7,800	Outside, mottled white and gray corrosion products - inside, dull gray
Aluminized improved plow steel	1 x 19, coating 0.0007 inch thick	0.313	14,200	-	-	13,000	Outside, gray with some white corrosion products - inside, dull gray

1/ Nominal value for improved plow steel

Table 10. Effect of Corrosion on Breaking Strengths of Stressed Wire Ropes

Designation	Condition	Diameter, Inch	Stress On Rope, Lb.	Breaking Load, Lb.			Remarks
				Original	751 Days, 5640 Feet	1064 Days, 5300 Feet	
Bright Plow Steel	Lubricated	0.325	2,100	10,700	10,700	11,500	Outside-100% rusted, inside-bright, cup and cone fracture[1]
Bright Monitor Steel	Lubricated	0.326	2,900	14,300	14,900	15,300	Outside-100% rusted, inside-bright, cup and cone fracture[1]
Galvanized Plow Steel	Lubricated, 0.83 oz. Zn	0.340	2,100	10,400	10,900	8,600	Outside-80% yellow-20% rust, inside-bright, cup and cone fracture[1]
Electrogalvanized	Lubricated, 1.50 oz. Zn	0.335	2,200	10,900	11,100	11,600	Outside-5% yellow-95% rust, inside-bright, cup and cone fracture[1]
Aluminized Steel	Unlubricated, 0.38 oz. Al	0.335	1,400	6,900	7,000	6,500	Outside-white corrosion products-50% rust; inside-95% bright-5% light rust stain, cup and cone fracture[1]
Type 316 Stainless Steel	Lubricated, 7 X 7	0.135	350	1,700	1,400	1,000	50% rust stains, broke at corrosion pits on internal wires[1]
Stainless Steel, 18% Cr - 14% Mn	Unlubricated, 7 X 19	0.395	2,500	12,400	11,400	12,500	Outside-considerable rust and broken wires, inside-some broken wires in all strands, 45° fractures[1]
PVC Coated Amgal	0.17 oz. Zn	0.125	250	1,300	1,200	1,100	PVC-dull, inside-some rust on wires-dull grey, cup and cone, and brittle fractures[1]

[1] After 1064 Days of Exposure

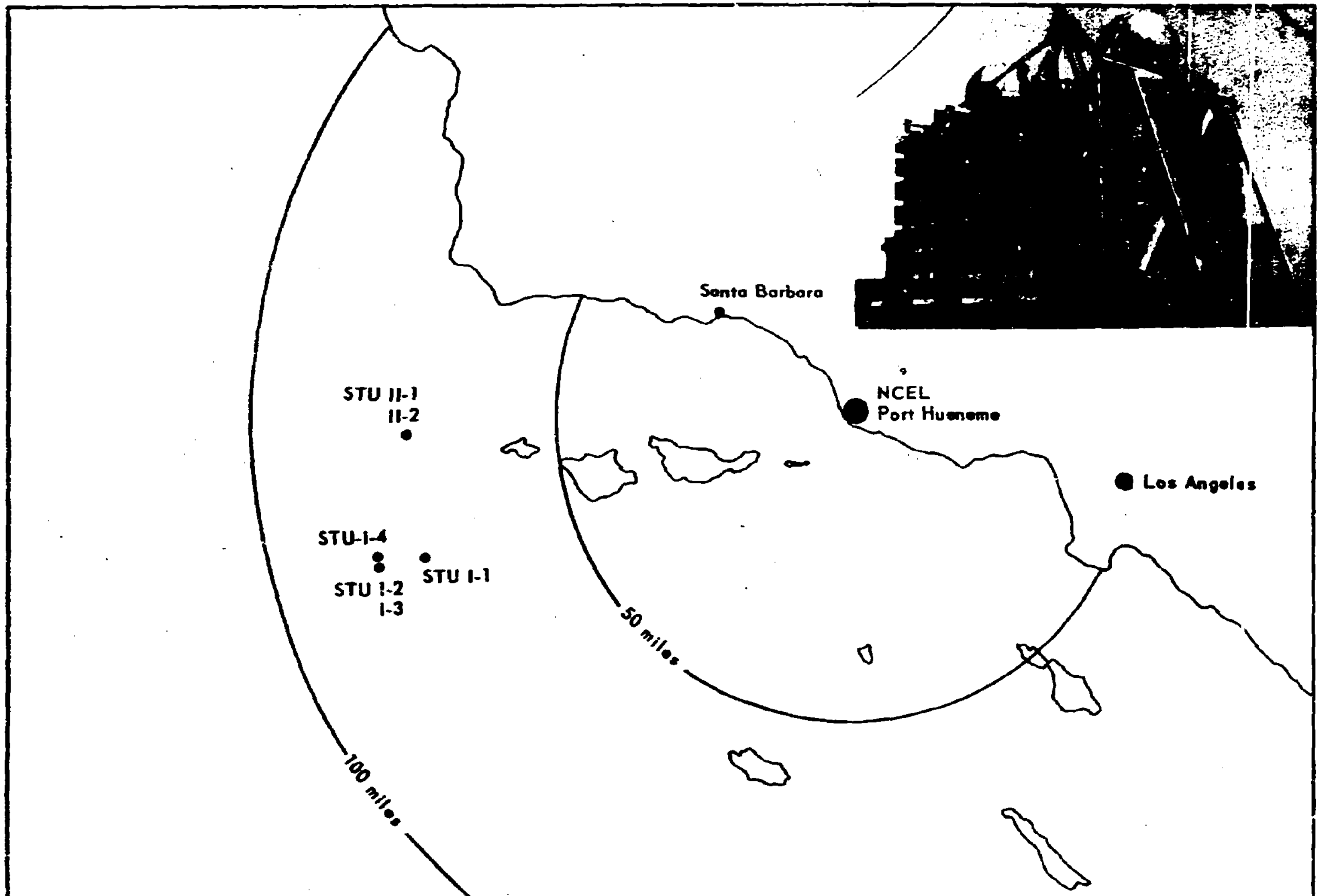

Figure 1. Area map showing STU sites off Pacific Coast; STU structure is inset.

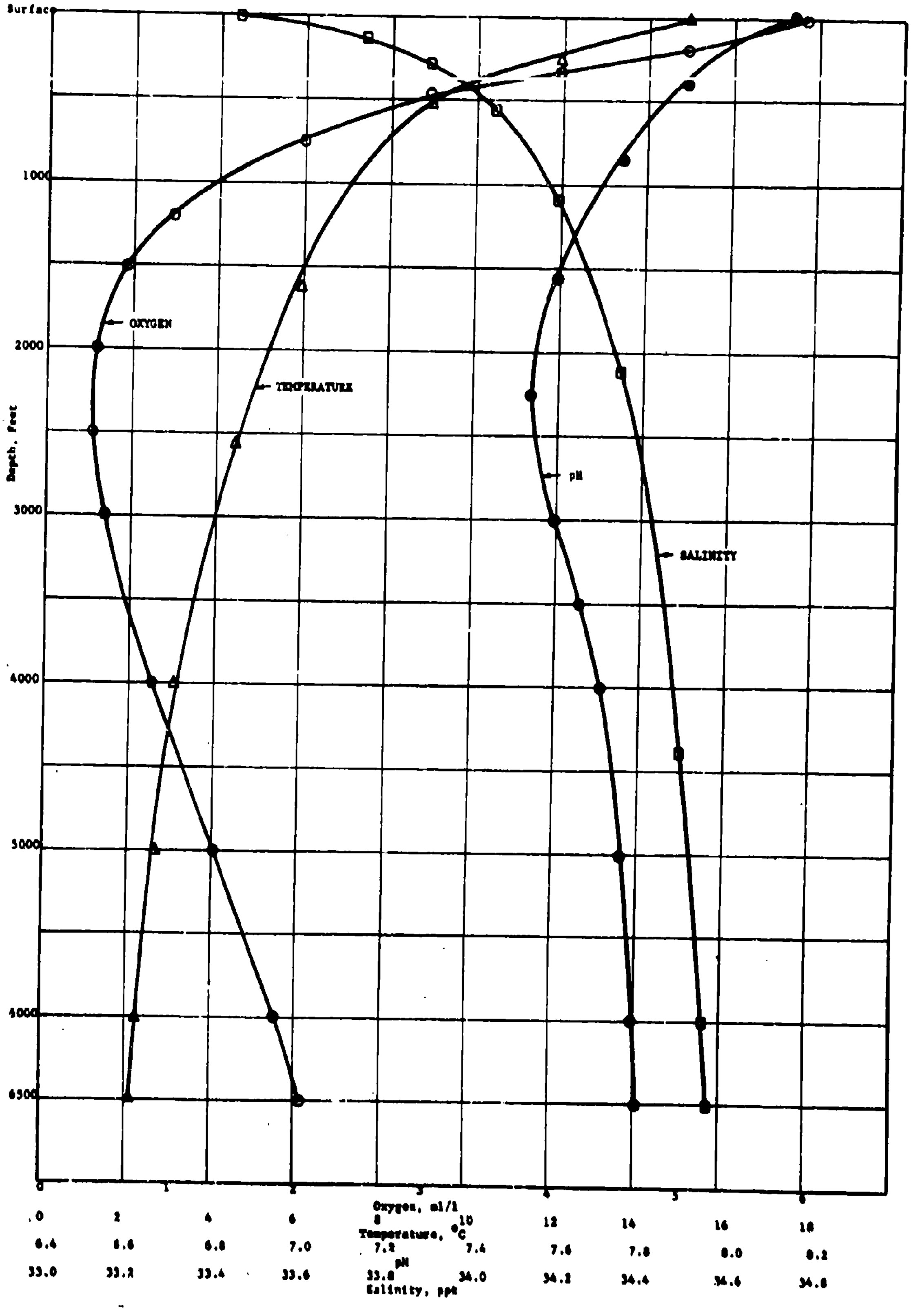

Figure 2. Oceanographic data at STU sites.

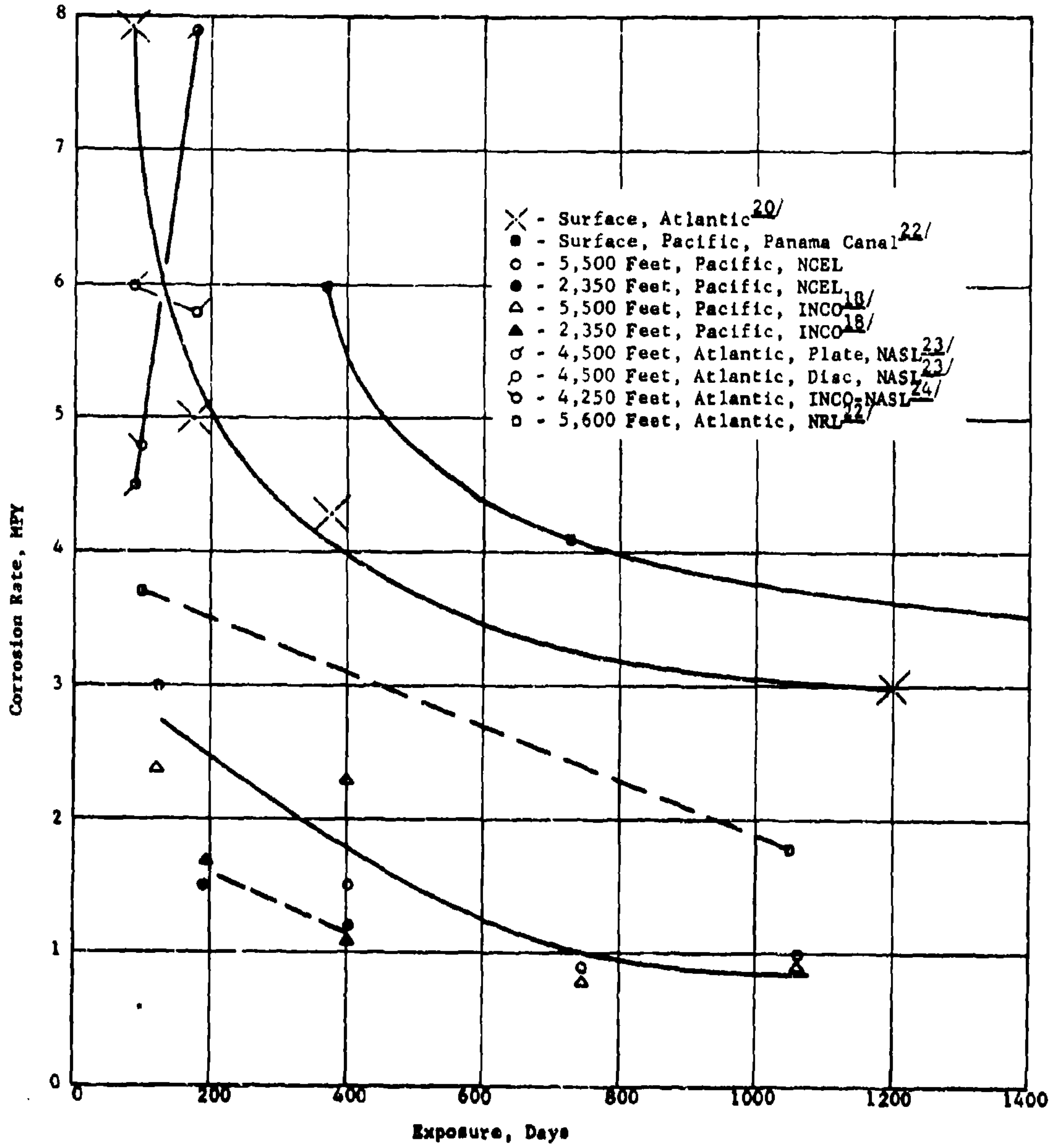

Figure 3. Corrosion rates of low carbon steels at various locations.

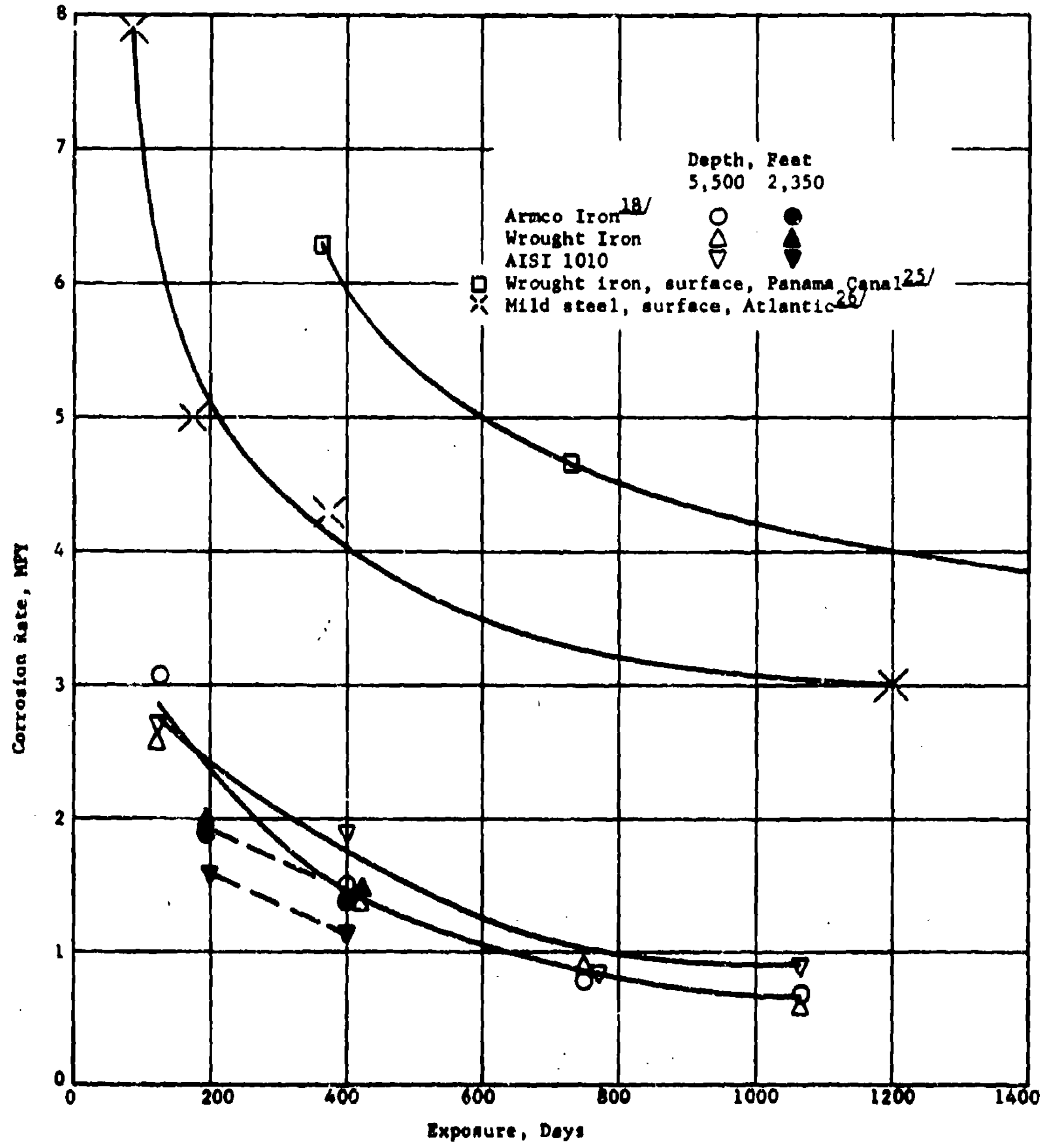

Figure 4. Corrosion rates of wrought iron and Armco iron in sea water.

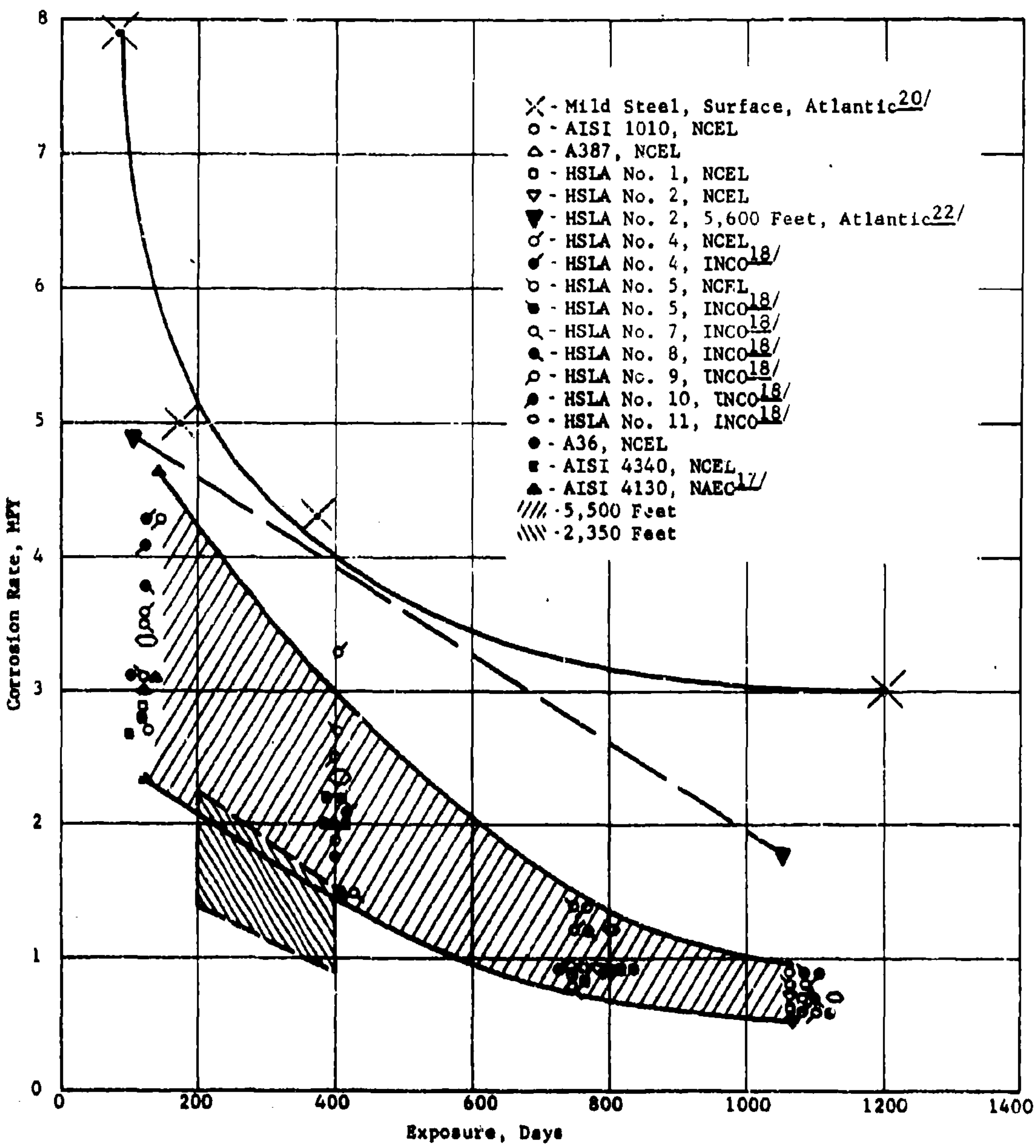

Figure 5. Corrosion rates of steels in sea water.

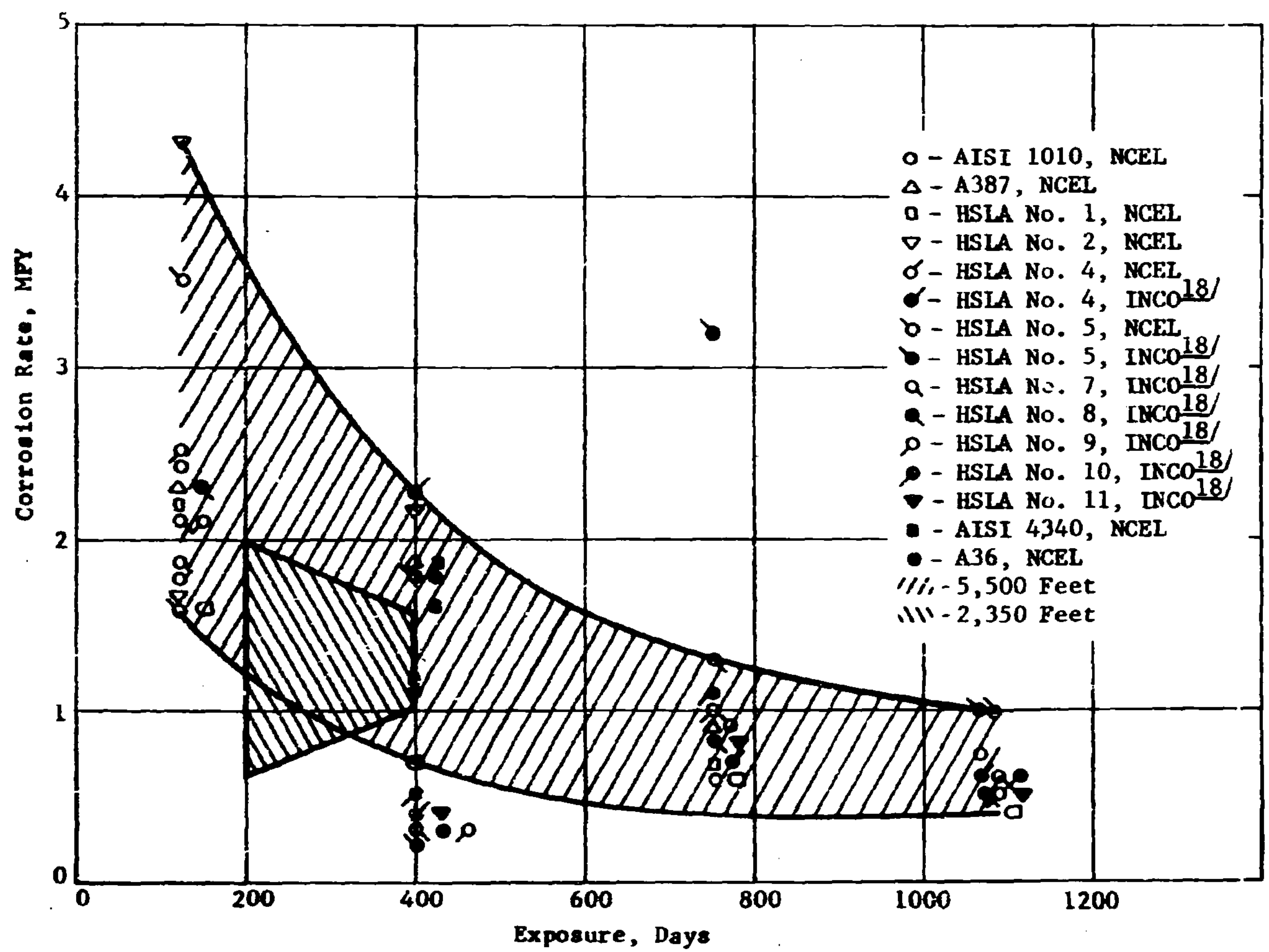

Figure 6. Corrosion rates of steels in the bottom sediments.

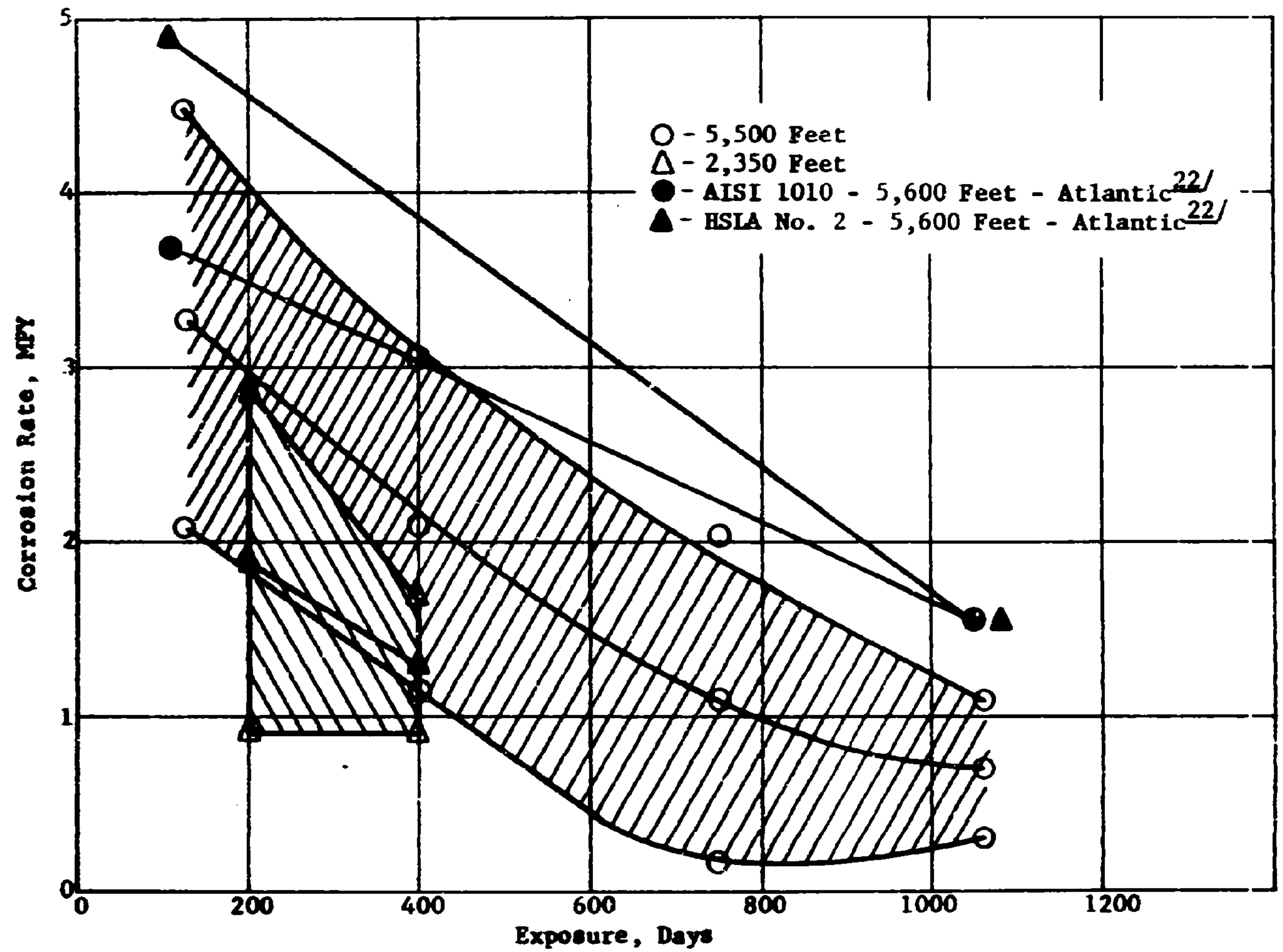

Figure 7. Statistical curves, 95 percent confidence limits, for steels in sea water.

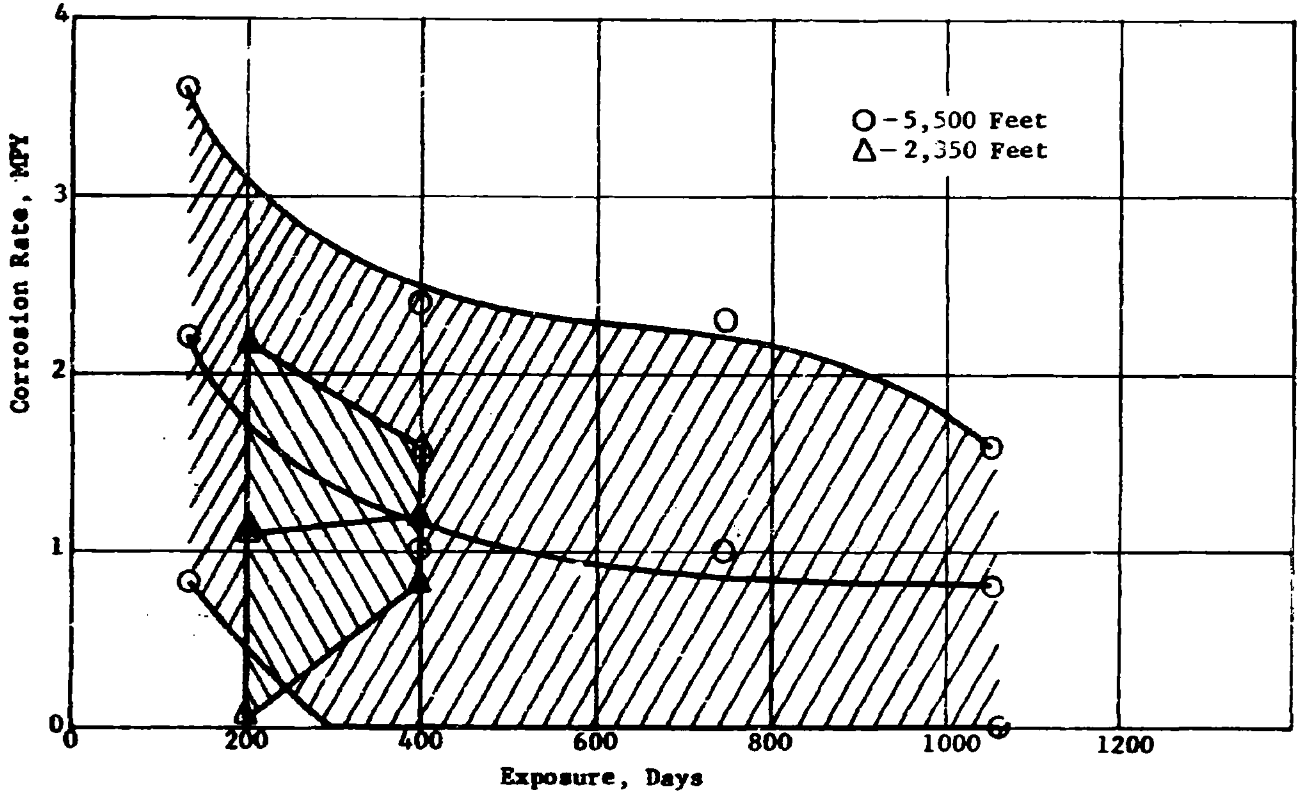

Figure 8. Statistical curves, 95 percent confidence limits, for the steels in the bottom sediments.

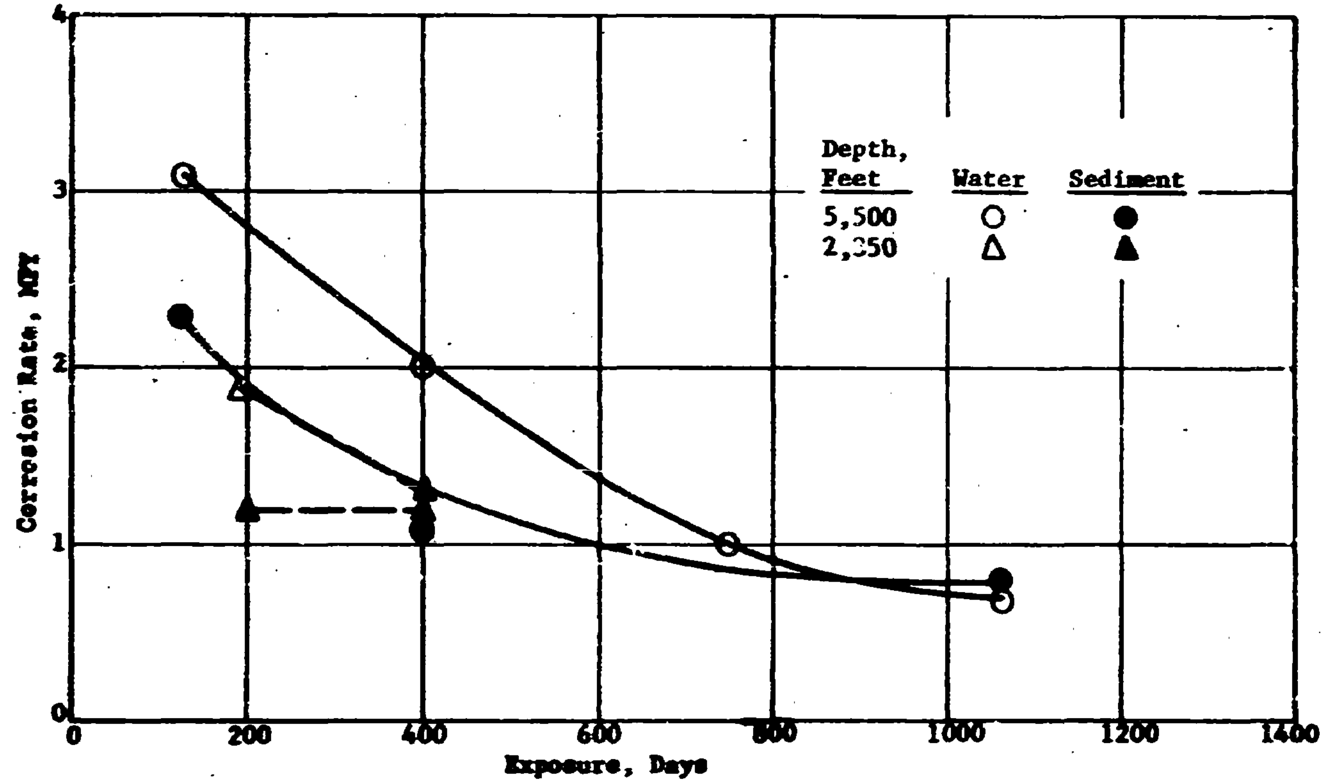

Figure 9. Median statistical curves for the steels in sea water and in the bottom sediments.

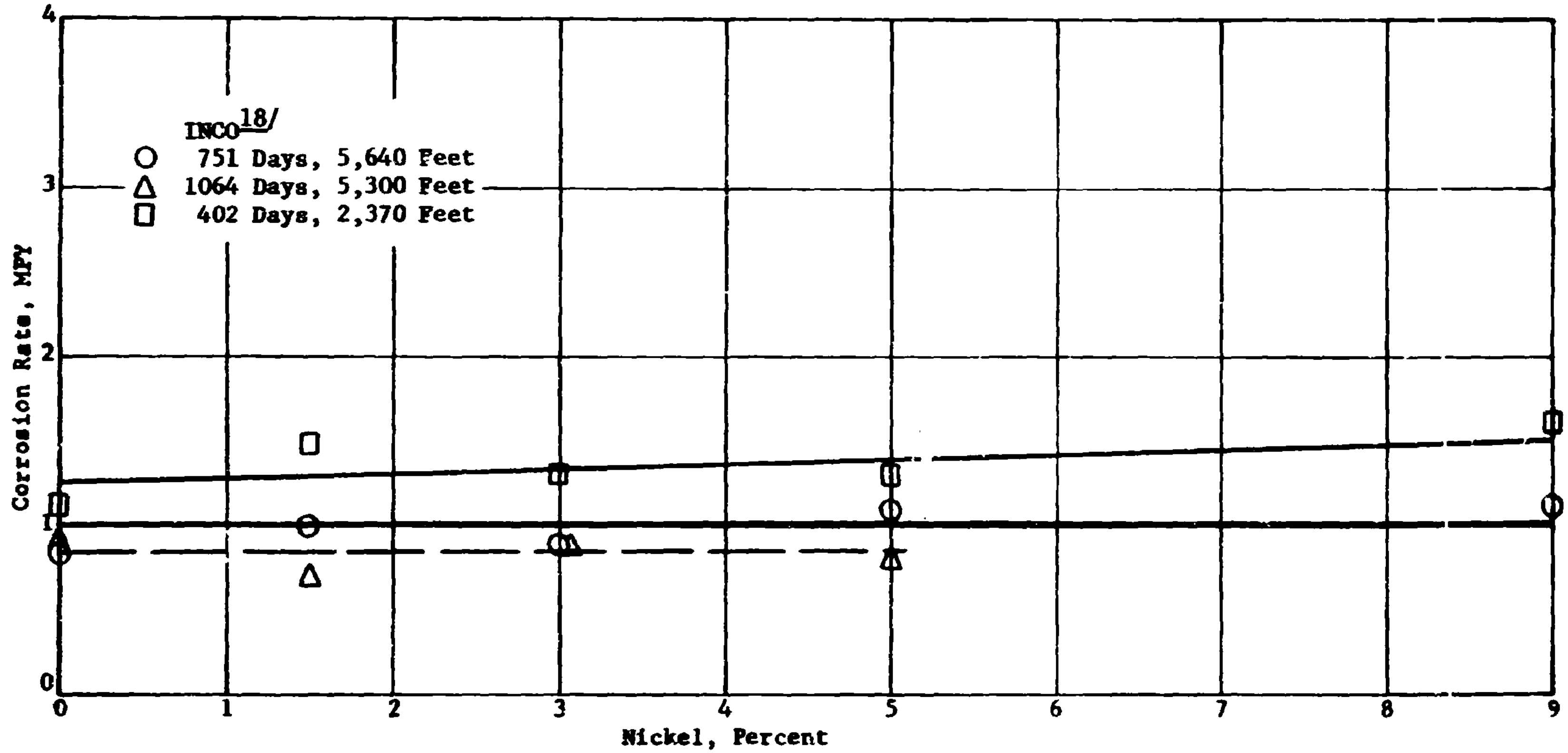

Figure 10. Effect of nickel on the corrosion rate of steel in sea water

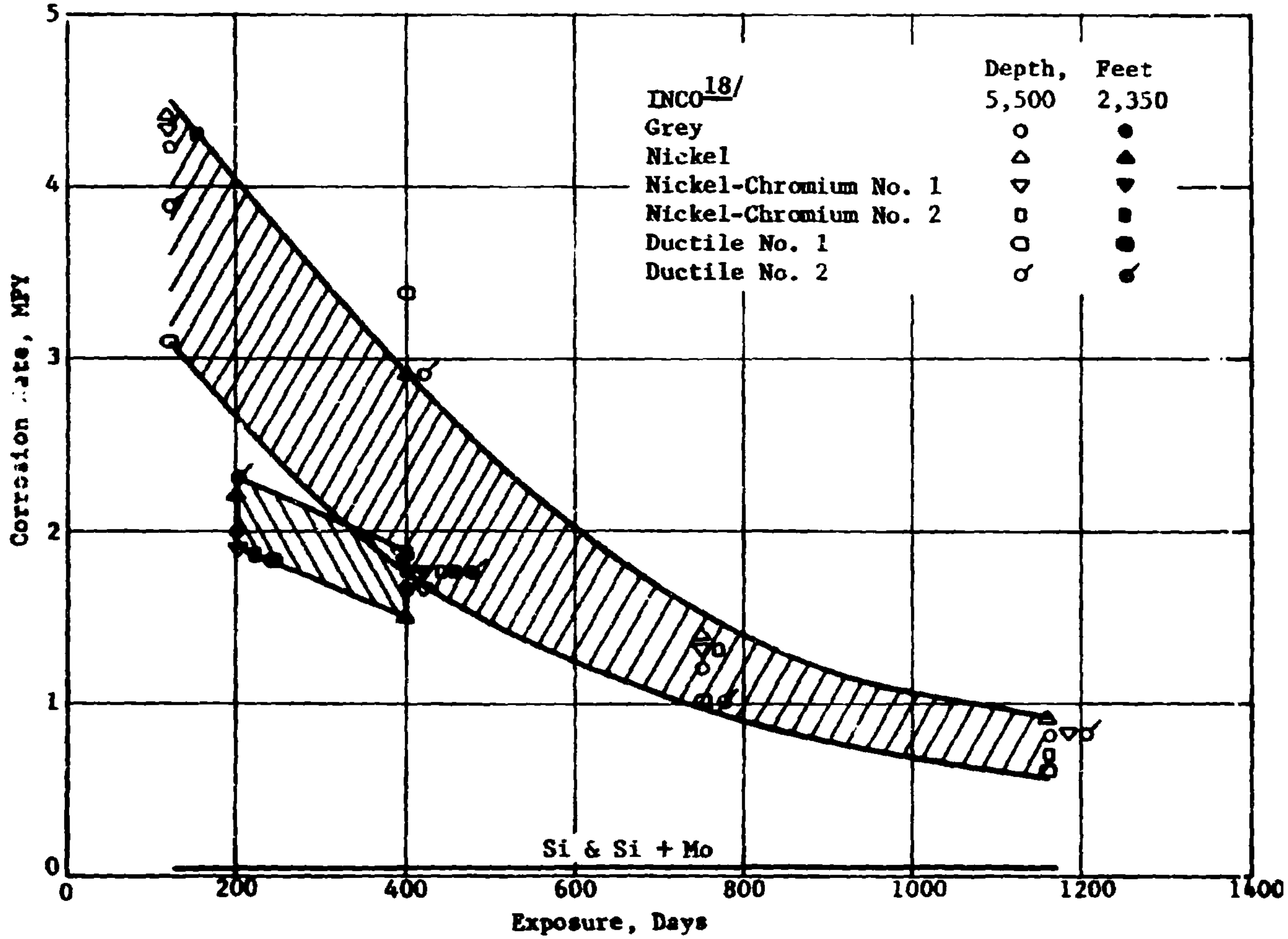

Figure 11. Corrosion rates of cast irons in sea water.

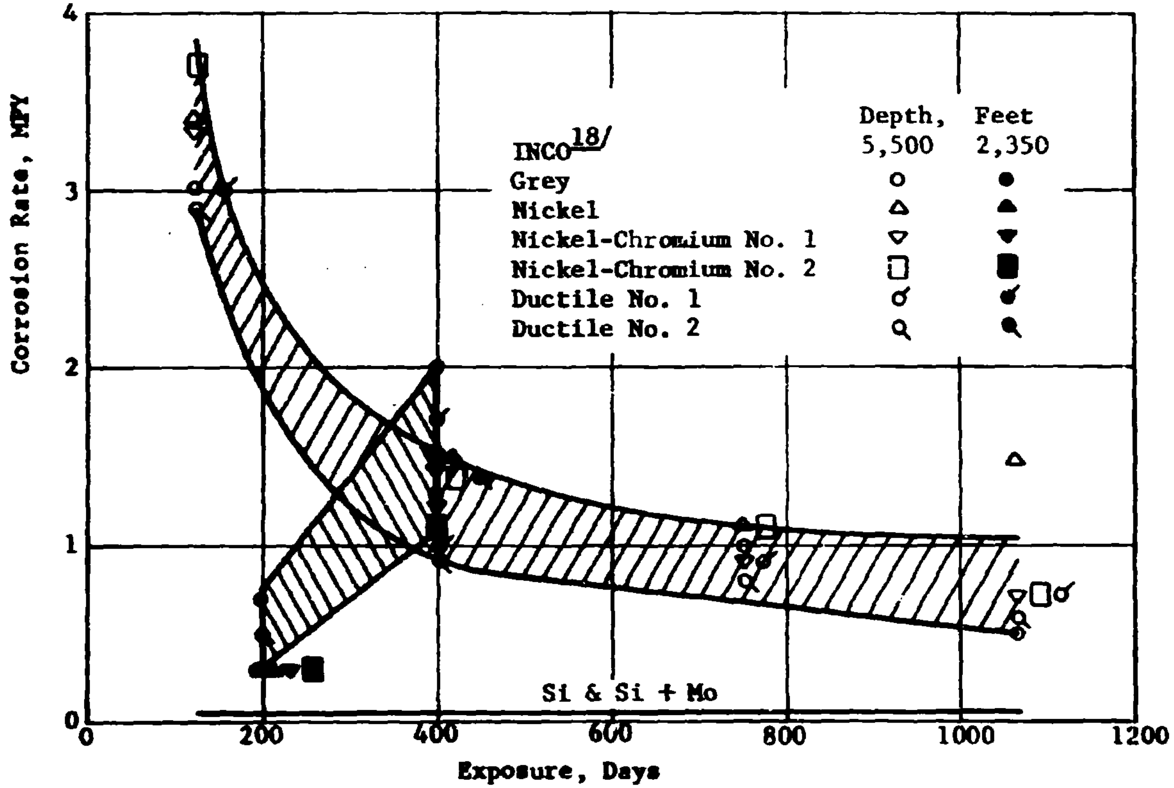

Figure 12. Corrosion rates of cast irons in the bottom sediments.

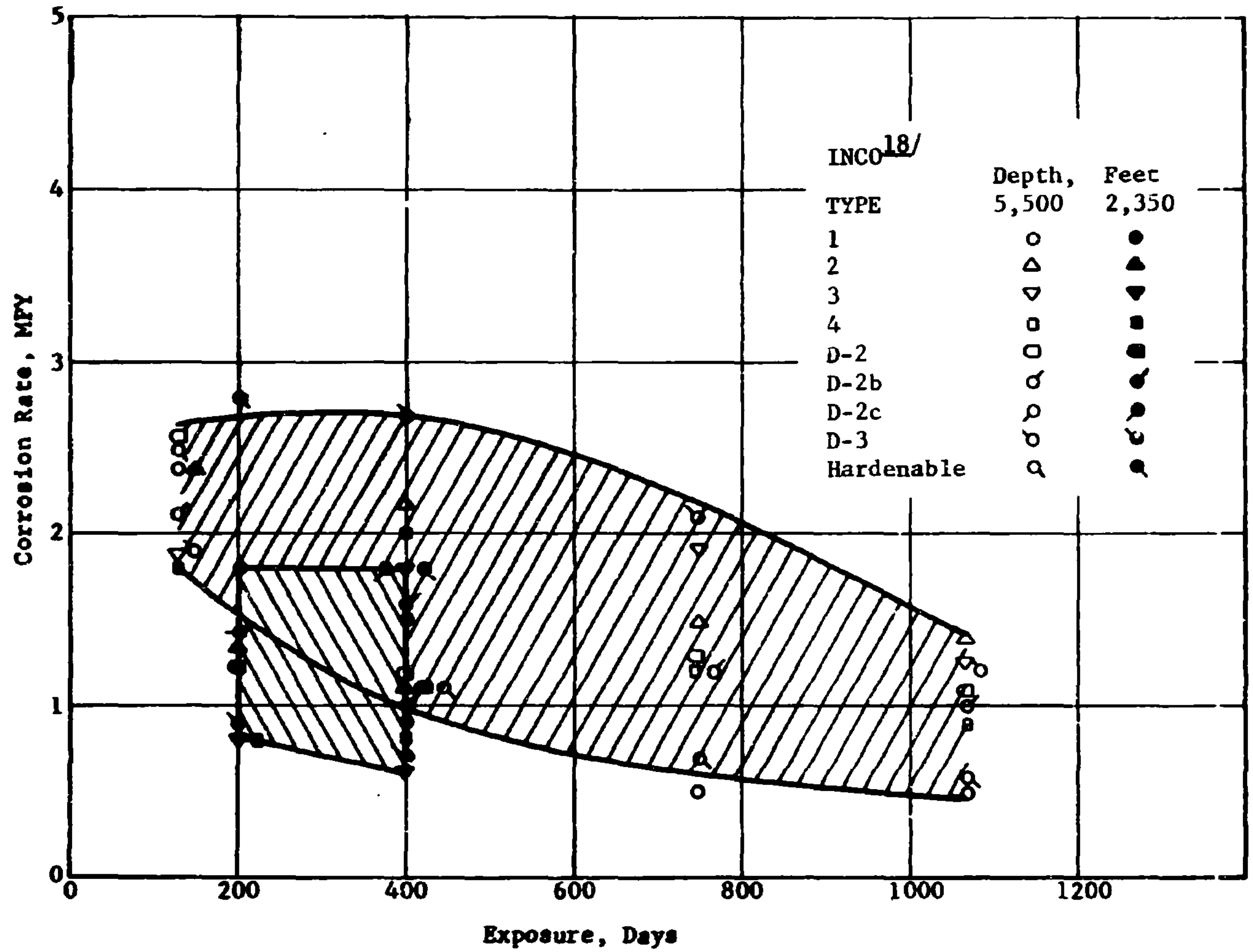

Figure 13. Corrosion rates of austenitic cast irons in sea water.

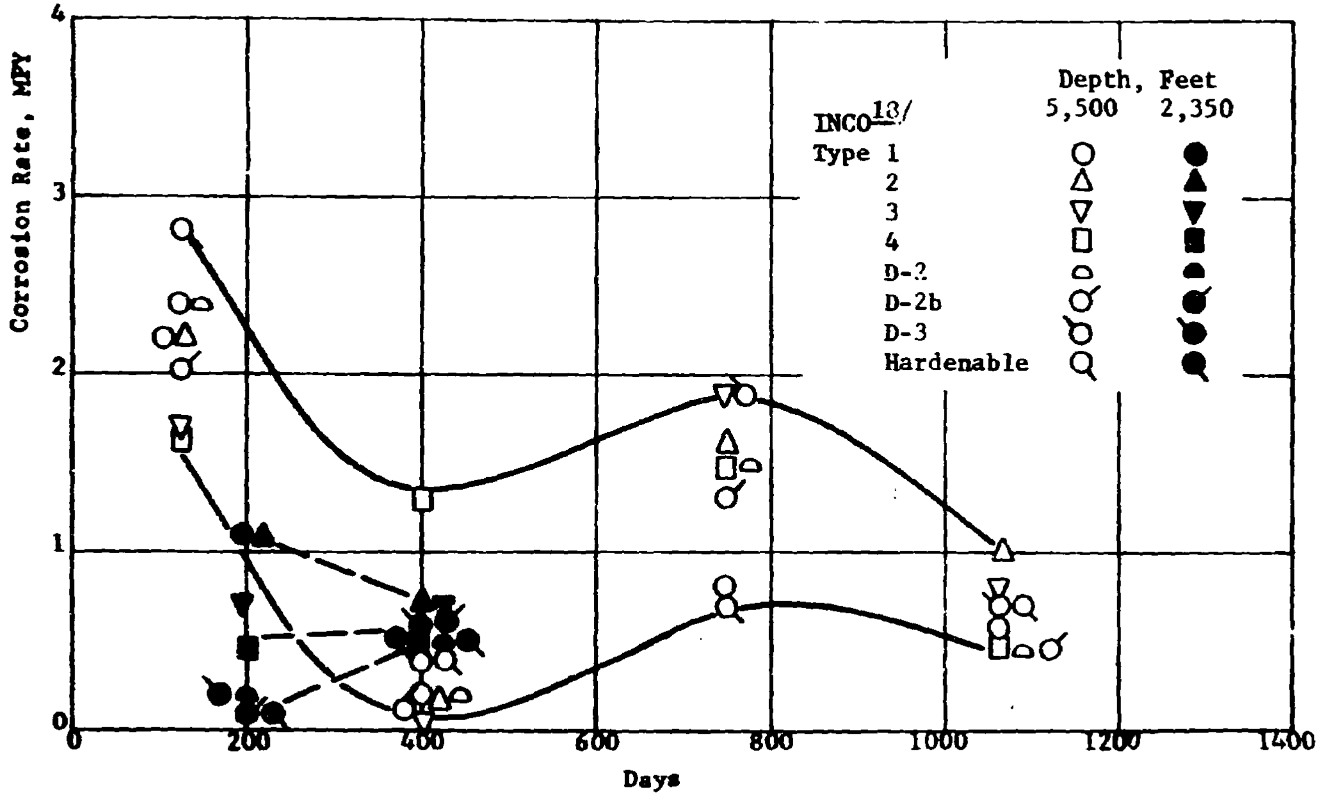

Figure 14. Corrosion rates of austenitic cast irons in the bottom sediments.

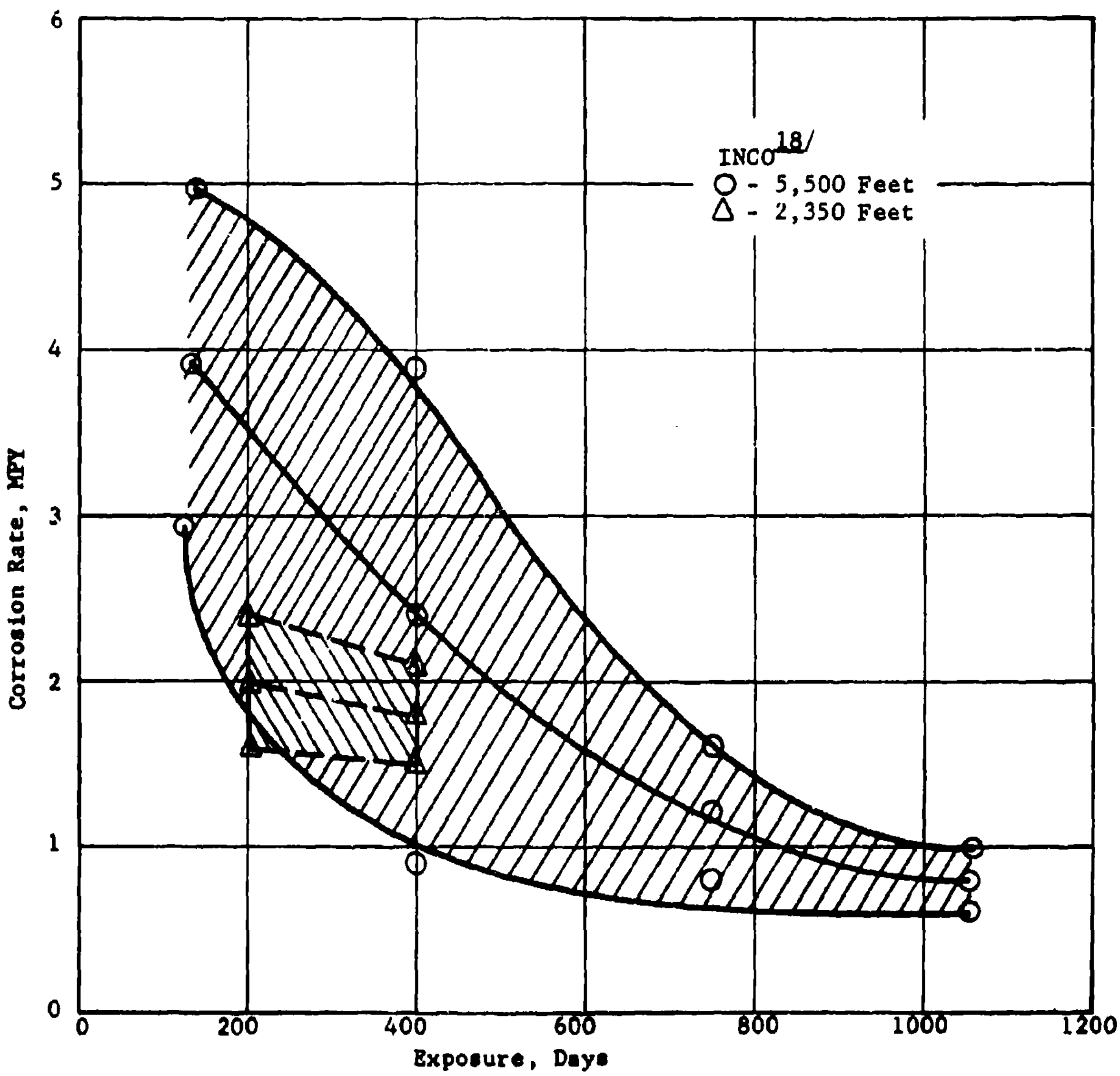

Figure 15. Statistical curves, 95 percent confidence limits, of cast irons in sea water.

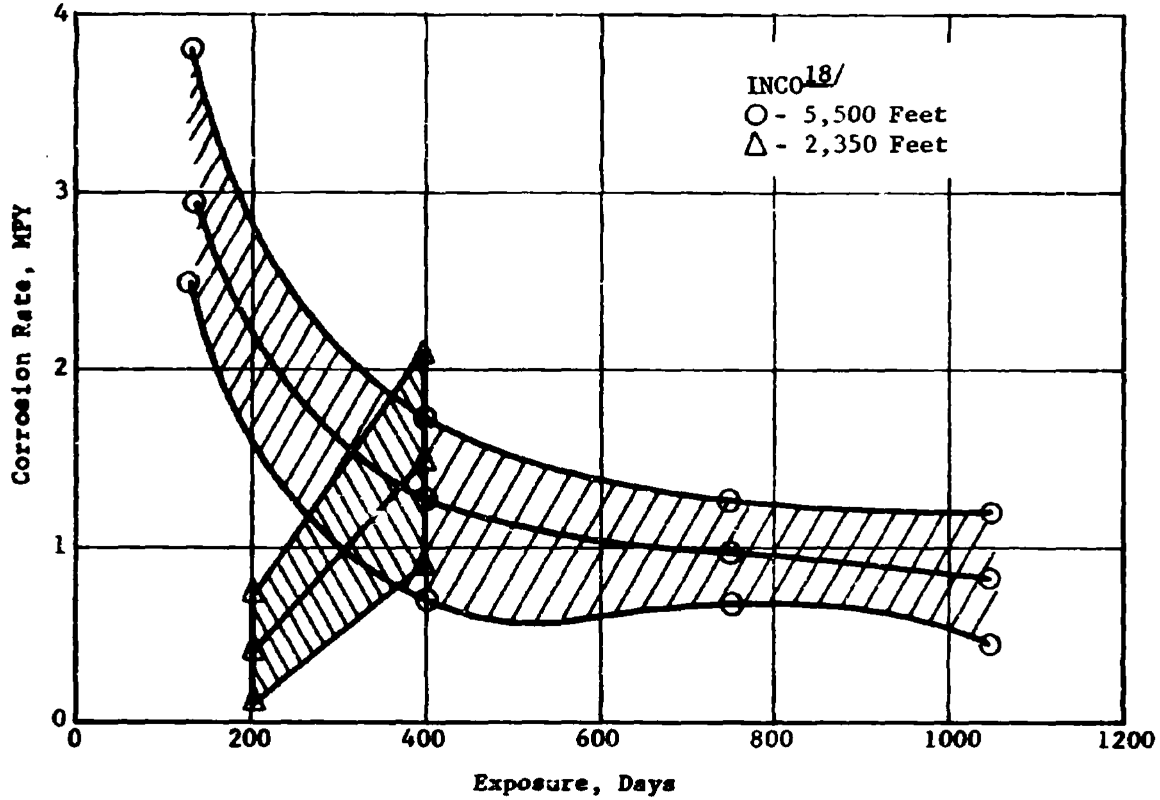

Figure 16. Statistical curves, 95 percent confidence limits, of cast irons in the bottom sediments.

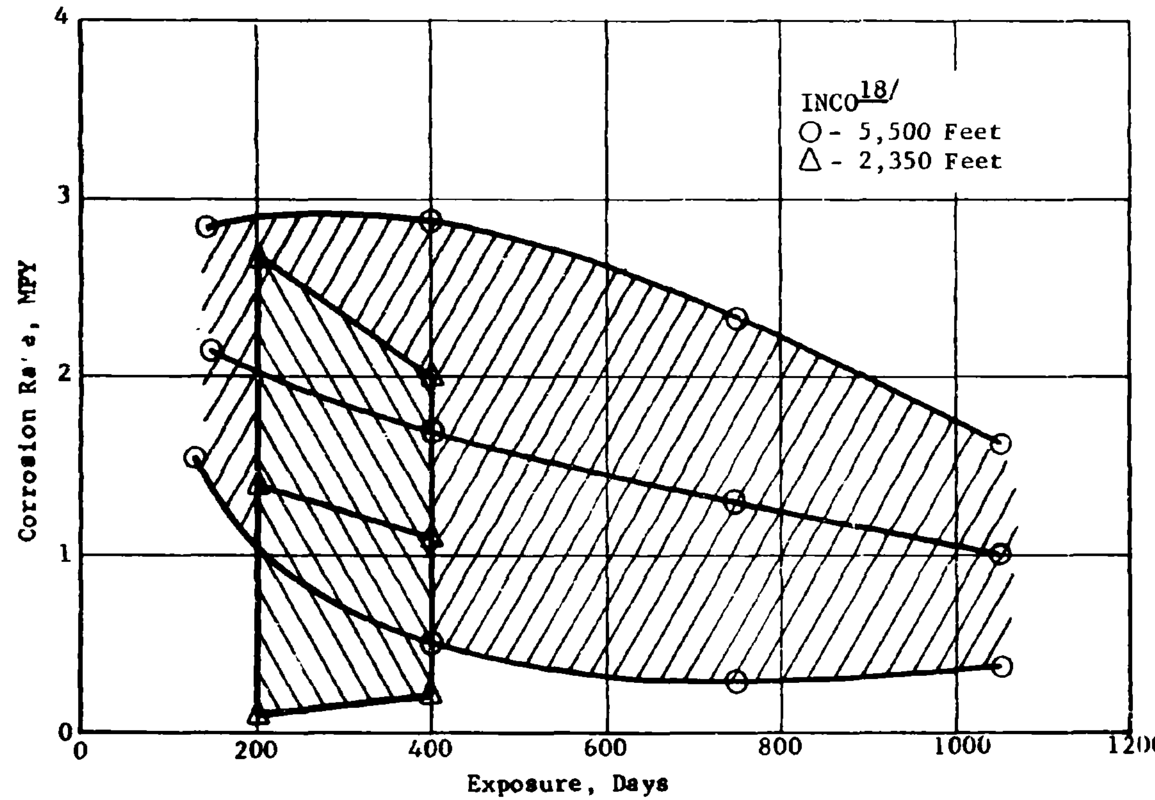

Figure 17. Statistical curves, 95 percent confidence limits, of austenitic cast irons in sea water.

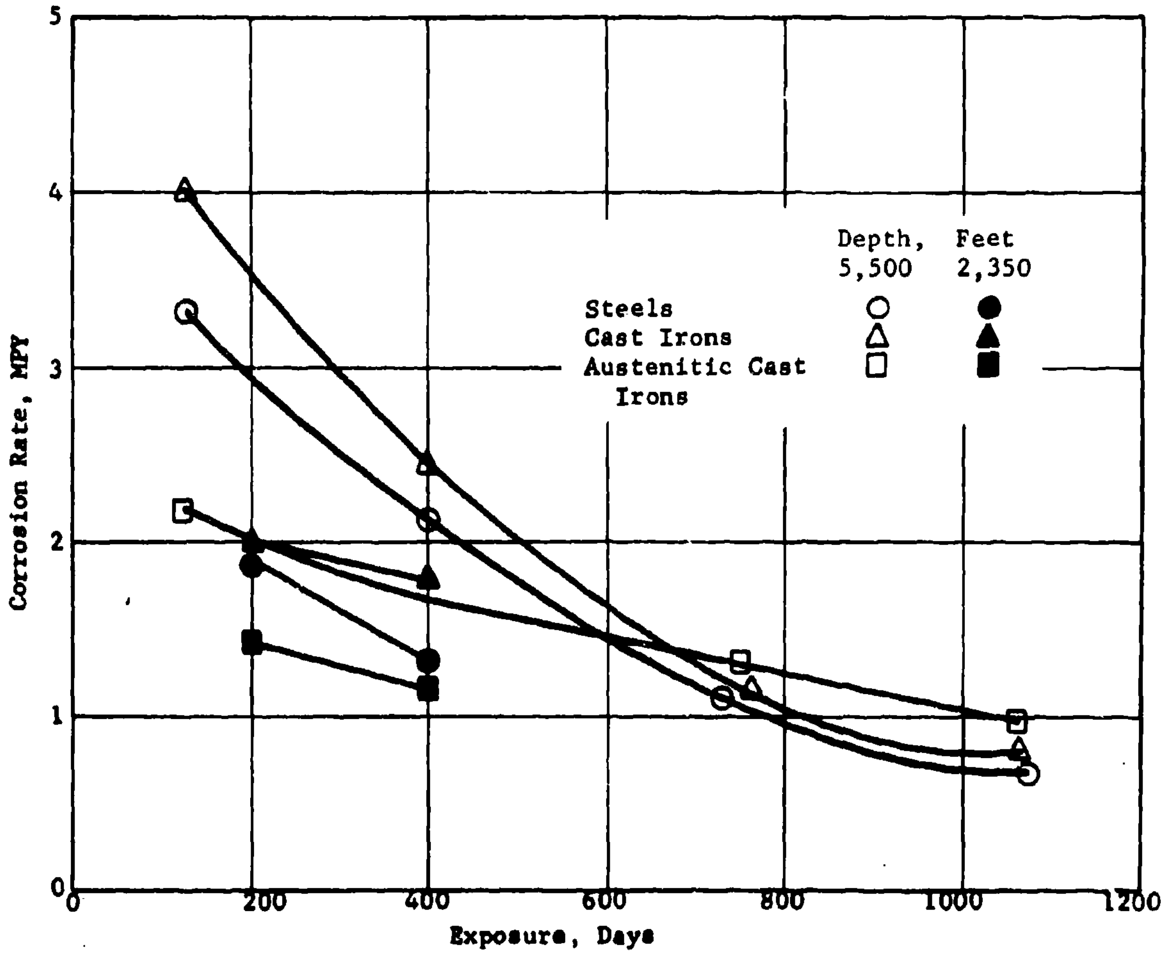

Figure 18. Statistical median curves for steels, cast irons and austenitic cast irons in sea water.

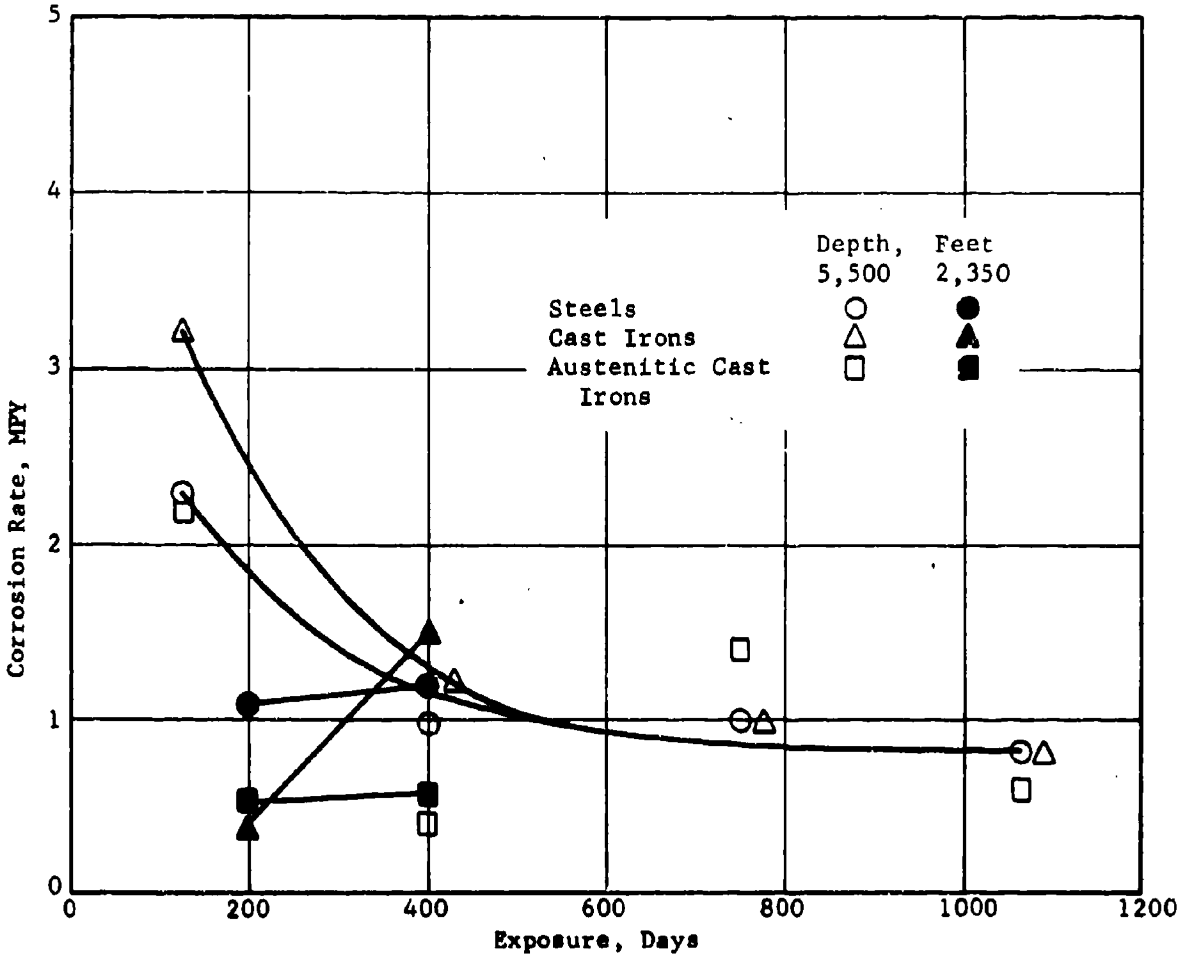

Figure 19. Statistical median curves for steels, cast irons and austenitic cast irons in the bottom sediments.

APPENDIX

MATHEMATICAL TREATMENT OF CORROSION DATA

The statistical median corrosion rate data for the steels after 400 days of exposure were treated by linear regression analysis to determine whether a mathematical expression could be obtained for calculating corrosion rates from oxygen concentration, temperature, and oxygen and temperature combined. The surface data were obtained from Figure 5 and the depth data from Figure 9.

A linear expression, $MPY = 0.5176 \cdot O_2 + 1.127$, was obtained for the effect of oxygen.

MPY = mils penetration per year

O_2 = concentration of oxygen in milliliters per liter of sea water.

Corrosion rates calculated using this expression agreed very well with those calculated from weight loss determinations after 400 days of exposure as shown in Figure 1. The corrosion rates of the steels increased linearly with oxygen concentration.

However, this expression is not applicable to other exposure time periods; for example, after 200 or 300 days of exposure. Curves of experimental corrosion rates for 200 and 300 days of exposure are not straight lines as shown in Figure 1. For these time periods, the corrosion rates of steels do not increase linearly with oxygen concentration; they more closely approach a hyperbolic relationship.

Uncorroded steels corrode at high rates when first immersed in sea water or any oxygenated electrolyte because of the free access of the dissolved oxygen to the surface of the steel. As the time of exposure increases and the film of corrosion products forms, the corrosion rate decreases because the access of oxygen to the uncorroded surface is impeded by the corrosion product film. When the film of corrosion products becomes of such a thickness and permeability that oxygen diffuses to the surface at a constant rate, the corrosion of the steel becomes constant with time and is known as being under diffusion control. This explains the non-linear increase in corrosion rates of steels with increase in oxygen concentration after only 200 or 300 days of exposure; i.e., they were not completely under diffusion control.

Corrosion rates calculated from exponential expressions for temperature and temperature and oxygen combined did not agree with experimental corrosion rates.

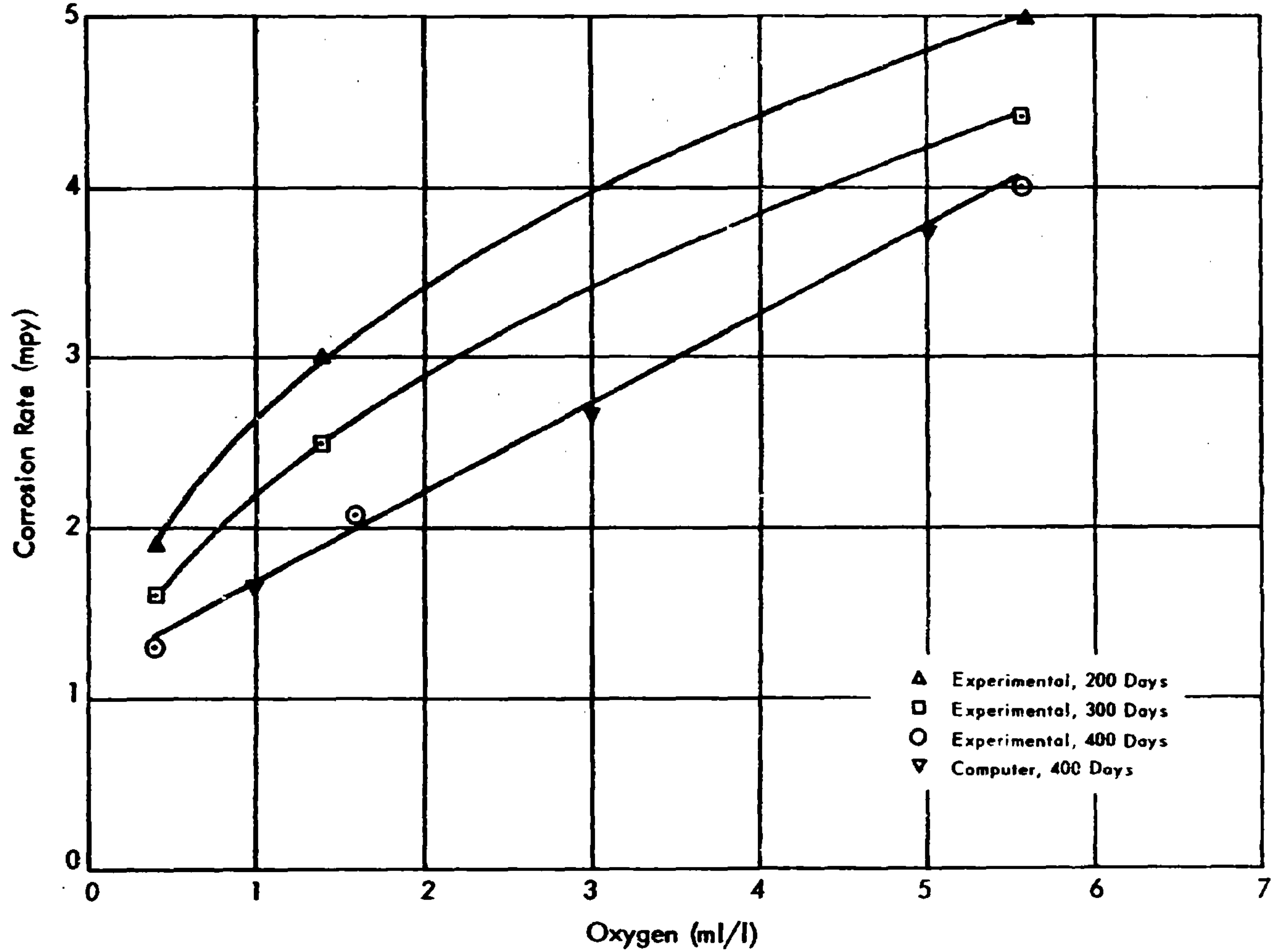

Figure A-1. Effect of oxygen on the corrosion of steels.

REFERENCES

1. U. S. Naval Civil Engineering Laboratory Technical Note N-446: "Effects of the Deep Ocean Environment on Materials - A Progress Report" by K. O. Gray, Port Hueneme, Calif., July 1962.

2. U. S. Naval Civil Engineering Laboratory Technical Note N-657: "Environment of the Deep Ocean Test Sites (Nominal Depth 6,000 feet) Latitude 33°46'N, Longitude 120°37'W" by K. O. Gray, Port Hueneme, Calif., Feb 1965.

3. U. S. Naval Civil Engineering Laboratory, Unpublished Oceanographic Data Reports, by K. O. Gray, Port Hueneme, Calif.

4. U. S. Naval Civil Engineering Laboratory Technical Report R-182: "The Effects of Marine Organisms on Engineering Materials for Deep Ocean Use" by J. S. Muraoka, Port Hueneme, Calif., Mar 1962.

5. U. S. Naval Civil Engineering Laboratory Technical Report R-329: "Deep Ocean Biodeterioration of Materials - Part I. Four Months at 5,640 feet" by J. S. Muraoka, Port Hueneme, Calif., Nov 1964.

6. U. S. Naval Civil Engineering Laboratory Technical Report R-358: "Deterioration of Rubber and Plastic Insulation by Deep-Ocean Organisms" by J. S. Muraoka, Port Hueneme, Calif., Mar 1965.

7. U. S. Naval Civil Engineering Laboratory Technical Report R-428: "Deep Ocean Biodeterioration of Materials - Part III. Three Years at 5,300 Feet" by J. S. Muraoka, Port Hueneme, Calif., Feb 1966.

8. U. S. Naval Civil Engineering Laboratory Technical Report R-456: "Deep Ocean Biodeterioration of Materials - Part IV. One Year at 6,800 Feet" by J. S. Muraoka, Port Hueneme, Calif., Jun 1966.

9. U. S. Naval Civil Engineering Laboratory Technical Note N-458: "Emplacement of the First Submersible Test Unit on the Sea Floor - One Mile Deep" by R. E. Jones, Port Hueneme, Calif., Feb 1963.

10. U. S. Naval Civil Engineering Laboratory Technical Report R-369: "Design, Placement and Retrieval of Submersible Test Units at Deep Ocean Test Sites" by R. E. Jones, Port Hueneme, Calif., May 1965.

11. U. S. Naval Civil Engineering Laboratory Technical Note N-705: "Retrieval of STU II-1 by Acoustical Method Beacon" by R. E. Jones and R. Krutenat, Port Hueneme, Calif., Nov 1966.

12. U. S. Naval Civil Engineering Laboratory Technical Note N-782: "Recovery of Submersible Test Unit I-1" by C. K. Paul, Port Hueneme, Calif., Oct 1965.

13. U. S. Naval Civil Engineering Laboratory Technical Report R-504: "Corrosion of Materials in Hydrospace" by Fred M. Reinhart, Port Hueneme, Calif., Dec 1966.

14. U. S. Naval Civil Engineering Laboratory Technical Note N-605: "Preliminary Examination of Materials Exposed on STU I-3 in the Deep Ocean - (5,640 Feet of Depth for 123 Days)," by Fred M. Reinhart, Port Hueneme, Calif., Jun 1964.

15. U. S. Naval Civil Engineering Laboratory Technical Note N-695: "Examples of Corrosion of Materials Exposed on STU II-1 in the Deep Ocean (2,340 Feet of Depth for 197 Days)" by Fred M. Reinhart, Port Hueneme, Calif., Feb 1965.

16. U. S. Naval Civil Engineering Laboratory Technical Note N-781: "Effect of Deep Ocean Environments on the Corrosion of Selected Alloys" by Fred M. Reinhart, Port Hueneme, Calif., Oct 1965.

17. U. S. Naval Civil Engineering Laboratory Technical Note N-793: "Visual Observations of Corrosion of Materials on STU I-1 After 1,064 Days of Exposure at a Depth of 5,300 Feet in the Pacific Ocean" by Fred M. Reinhart, Port Hueneme, Calif., Nov 1965.

18. Dr. T. P. May, unpublished data.

19. Naval Air Engineering Center, Aeronautical Materials Laboratory Report No. NAEC-AML-2132 "Evaluation of Metallic Materials Exposed to the Deep Ocean Environment at 5,640 Feet for 123 Days" by John J. De Luccia and Edward Taylor, Philadelphia, Pa., 22 Jun 1965.

20. Dr. T. P. May, personal correspondence.

21. Naval Research Laboratory Report 5153, "Corrosion of Metals in Tropical Environments, Part 3 - Underwater Corrosion of Ten Structural Steels" by B. W. Forgeson, C. R. Southwell and A. L. Alexander, Washington, D. C., 8 Aug 1958.

22. Naval Research Laboratory Memorandum Report 1634, "Marine Corrosion Studies - Third Interim Report of Progress" by B. F. Brown and others, Washington, D. C., Jul 1965.

23. Naval Applied Science Laboratory Report, "Corrosion at 4,500 Foot Depth in Tongue-of-the-Ocean" SR004-03-01, Task 0589, Lab. Project 9400-72, Technical Memorandum 3, by E. Fischer and S. Finger, Brooklyn, New York, Mar 1966.

24. Naval Applied Science Laboratory Report "Retrieval, Examination and Evaluation of Materials Exposed for 102 Days on NASL Deep Sea Materials Exposure Mooring No. 1", SF 099-03-01, Task 1481 and (SF-02-030-06 Task 1003) Lab. Project 9300-6, Technical Memorandum 4 (and Lab. Project 9300-7), A. Anaustasio, Brooklyn, New York, Nov 1965.

25. Naval Research Laboratory Report 5370, "Corrosion of Metals in Tropical Environments, Part 4 - Wrought Iron" by C. R. Southwell, B. W. Forgeson and A. L. Alexander, Washington, D. C., Oct 1959.

26. A. C. Redfield. "Characteristics of Sea Water", in Corrosion Handbook, edited by H. H. Uhlig. New York, Wiley, 1948, p. 1111.

27. F. L. LaQue. "Behavior of Metals and Alloys in Sea Water," in Corrosion Handbook, edited by H. H. Uhlig. New York, Wiley, 1948, p. 390.

28. C. P. Larrabee. "Corrosion Resistance of High-strength-low-alloy Steels as Influenced by Composition and Environment," Corrosion, Vol. 9, No. 8, Aug 1953, pp. 259-271.

29. F. L. LaQue and H. R. Copson, "Corrosion Resistance of Metals and Alloys" Second Edition, ACS Monograph No. 158, Reinhold Publishing Corp., New York, New York, 1963, pp. 74-76.

30. H. H. Uhlig "Corrosion and Corrosion Control" John Wiley and Sons, Inc., New York, 1963, p. 80-85.

31. L. L. Schreir "Corrosion", Vol. 1, John Wiley and Sons, New York, 1963, p. 232.

32. L. L. Schreir "Corrosion", Vol. 1, John Wiley and Sons, New York, 1963, p. 227.

33. U. S. Naval Research Laboratory. NRL Memorandum Report 1383, "Abyssal Corrosion and Its Mitigation - Part II, Results of A Pilot Exposure Test" by B. W. Forgeson, et al, Washington, D. C., Dec 1962.

34. U. S. Naval Civil Engineering Laboratory Technical Note N-859: "Corrosion Rates of Selected Alloys in the Deep Ocean" by W. S. Haynes, Ph.D. and J. B. Crilly, Port Hueneme, Calif., 17 Nov 1966.

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13. ABSTRACT

A total of 1300 specimens of 47 iron base alloys were exposed at depths of 2,340, 2,370, 5,300, 5,640 and 6,780 feet at two sites in the Pacific Ocean for 197, 402, 1064, 123, 751 and 403 days respectively to determine the effects of deep ocean environments on their corrosion behavior.

Corrosion rates, pit depths, types of corrosion, changes in mechanical properties, effects of stress, and analyses of corrosion products are presented.

The corrosion rates of all the alloys, both cast and wrought, decreased asymptotically with duration of exposure and became constant at rates varying between 0.5 and 1.0 mils per year after three years of exposure in sea water and partially embedded in the bottom sediments at a nominal depth of 5,500 feet. These corrosion rates are about one-third those at the surface in the Atlantic Ocean.

At the 2,350 foot depth, the corrosion rates in sea water also decreased with duration of exposure but tended to increase slightly with duration of exposure in the bottom sediments.

The corrosion rates at the 2,350 foot depth were less than those at the 5,500 foot depth.

The mechanical properties were unimpaired.

Silicon and silicon-molybdenum cast irons were uncorroded.

A sprayed 6 mil thick coating of aluminum protected steel for a minimum of three years and a hot dipped 4 mil thick coating of aluminum protected steel for a minimum of 13 months while a hot dipped 1.7 mil thick coating of zinc protected steel for about 4 months.

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